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The course presented in this report is designed for engineers and professional personnel responsible for measuring air pollution levels or for measuring and evaluating meteorological parameters which affect the diffusion and concentration of pollutants in the atmosphere. Instruction provides the trainee with a knowledge of the effects of meteorology on air pollution. He learns the role of meteorology in the transport and diffusion of air pollution, calculates estimates of pollutant concentrations for continuous releases, and studies meteorological instrumentation and correct instrument exposure.

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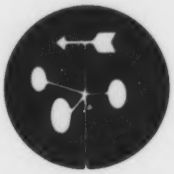
Air Pollution Meteorology



This course is designed for engineers and professional personnel responsible for measuring air pollution levels or for measuring and evaluating meteorological parameters which affect the diffusion and concentration of pollutants in the atmosphere. Instruction provides the trainee with a knowledge of the effects of meteorology on air pollution. He learns the role of meteorology in the transport and diffusion of air pollution, calculates estimates of pollutant concentrations for continuous releases, and studies meteorological instrumentation and correct instrument exposure. The instruction also enables him to discuss the important factors related to site selection, control programs, and the planning and interpreting of surveys. Discussions concern sources of meteorological information and the availability of additional professional assistance. This training manual has been specially prepared for the trainees attending this course and should not be included in reading lists or periodicals as generally available.

Conducted by

Office of Manpower Development
Institute for Air Pollution Training

ENVIRONMENTAL PROTECTION AGENCY

Office of Air Programs
Research Triangle Park, North Carolina 27711

INSTITUTE FOR AIR POLLUTION TRAINING

OFFICE OF MANPOWER DEVELOPMENT

The Insititue for Air Pollution Training (1) conducts training for the development and improvement of State, regional, and local governmental air pollution control programs, (2) provides consultation and other training assistance to governmental agencies, educational institutions, industrial organizations, and others engaged in air pollution training activities and, (3) promotes the development and improvement of air pollution training programs in educational institutions and State, regional, and local governmental air pollution control agencies.

One of the principle mechanisms utilized to meet the Institute's goals is the intensive short term technical training course. A ful time professional staff is responsible for the design, development and presentation of these courses. In addition the services of scientists, engineers and specialists from other NAPCA programs, governmental agencies, industry and universities are used to augment and reinforce the Institute staff in the development and presentations of technical material.

Individual course objectives and desired learning outcomes are delineated to meet specific training needs. Subject matter areas covered include process evaluation and control, atmospheric sampling and analysis, field studies and air quality management. These courses are presented in the Institute's resident classrooms and laboratories and at various field locations

Harry P. Kramer

Harry P. Kramer, Sc.D.
Director, Office of Manpower Development

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Course Objectives.....

At the conclusion of this course the trainee should:

1 Know the primary effects of meteorology on air pollution and the effects of air pollution on meteorology, emphasizing the former.

2 Know the role of meteorology in the transport and diffusion of air pollutants.

3 Know the Pasquill-Gifford method for estimating pollutant concentrations from continuous releases and the limitations of the method.

4 Know what the primary meteorological instruments used in air pollution work are, their operating characteristics, and correct exposure of them.

5 Know the important meteorological factors that should be considered in site selection, control programs, and in planning and interpreting surveys.

6 Be familiar with the current research activities in air pollution meteorology.

7 Know the important sources of meteorological information and how assistance on meteorological problems in air pollution may be obtained.

SECTION ONE

METEOROLOGICAL FUNDAMENTALS

Meteorological Fundamentals
Adiabatic Diagram

METEOROLOGIC FUNDAMENTALS

D. B. Turner*

RADIATION

The energy expended in the atmospheric processes originally was derived from the sun. This transfer of energy from the sun to the earth and its atmosphere is by radiation of heat by electromagnetic waves. The radiation from the sun has its peak of energy transmission in the visible range (0.4 to 0.7 microns) of the electromagnetic spectrum but releases considerable energy in the ultraviolet and infrared regions as well. The greatest part of the sun's energy is emitted at wave lengths between 0.1 and 30 microns. Some of this radiation is reflected from the tops of clouds and from the land and water surfaces of the earth. The general reflectivity is the albedo and for the earth and atmosphere as a whole is 36 per cent, for mean conditions of cloudiness over the earth. This reflectivity is greatest in the visible range of wavelengths. When light (or radiation) passes through a volume containing particles whose diameter is smaller than the wavelength of the light, scattering of a portion of this light takes place. Shorter wavelengths scatter most easily which is the reason the scattered light from the sky appears blue. Sunlight, near sunrise and sunset, when passing through a greater path-length of the atmosphere appears more red due to the increased scattering of shorter wave lengths. Absorption of solar radiation by some of the gases in the atmosphere (notably water vapor) also takes place. Water vapor, although comprising only 3 per cent of the atmosphere, on the average absorbs about six times as much solar radiation as all other gases combined. The amount of radiation received at the earth's surface is considerably less than that received outside the atmosphere.

The earth reradiates energy in proportion to its temperature according to Planck's law. Because of the earth's temperature, the maximum emission is about 10 microns, which is in the infrared region of the spectrum. The gases of the atmosphere absorb some wave length regions of this radiation. Water vapor absorbs strongly between 5.5 and 7 microns and at greater than 27 microns but is essentially transparent from 8 to 13 microns. Carbon dioxide absorbs strongly between 13 and 17.5 microns. Because of the absorption of much more of the terrestrial radiation by the atmosphere than of the solar radiation, some of the heat energy of the earth is conserved. This is the "greenhouse" effect.

Figure 1 shows as a function of latitude the amount of solar radiation absorbed by the earth and atmosphere compared to the long wave radiation leaving the atmosphere. The sine of the latitude is used as abscissa to represent area. It can be seen that if there were no transfer of heat poleward, the equitorial regions would continue to heat up and the polar regions continue to cool. Since the temperatures remain nearly the same for various areas of the earth, such a transfer does take place. The required transfer of heat across various latitudes is given in Table 1.

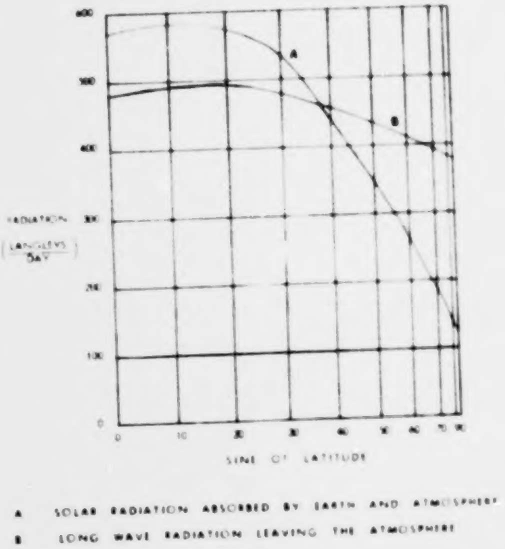

FIGURE 1

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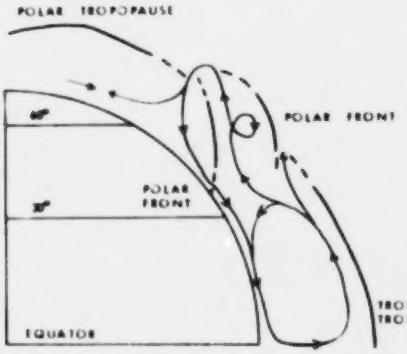
Table 1. Required Flux of Heat Toward the Poles Across Latitudes (10^{19} calories per day) From Houghton

Latitude	Flux
0	0
10	4.05
20	7.68
30	10.46
40	11.12
50	9.61
60	6.68
70	3.41
80	0.94
90	0

THE GENERAL CIRCULATION

The previous section has indicated the necessity of transfer of heat from the warm equatorial regions to the cold polar regions in order to maintain the heat balance of the atmosphere. This thermal driving force is the main cause of atmospheric motion on the earth. The rotation of the earth modifies this motion but does not cause it since the atmosphere essentially rotates with the earth. The portion of the earth near the equator acts as a heat source and the polar regions as a heat sink. The atmosphere functions as a heat engine transforming the potential energy of heat difference between tropics and poles to kinetic energy of motion which transports heat poleward from source to sink.

If the earth did not rotate, rising air above the equator would move poleward aloft where in giving up some of its heat would sink and return toward the equator as a surface current. Since the earth does rotate, the Coriolis force (to be discussed in the section on wind) deflects winds in the northern hemisphere to the right. Therefore flow from the tropics toward the poles become more westerly and flow from the poles toward the equator tends to become easterly. The result is that most of the motion is around the earth (zonal) with less than one-tenth of the motion between poles and equator. The meridional (along meridions i.e. between poles and equator) circulation is broken into three cells shown in Figure 2 according to Palmen's model. Of considerable importance is the fact that the jet stream does not remain long in one position but meanders and is constantly changing position. This causes changes in the location of the polar front and perturbations along the front. The migrating cyclones and anticyclones resulting, play an important part in the heat exchange, transferring heat northward both as a sensible heat and also latent heat. Also a small amount of heat is transferred poleward by the ocean currents.



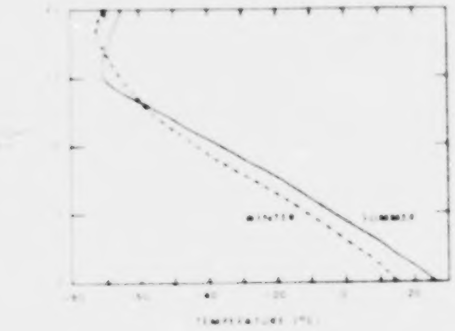
GENERAL CIRCULATION MODEL
(AFTER PALMEN)

FIGURE 2

TEMPERATURE

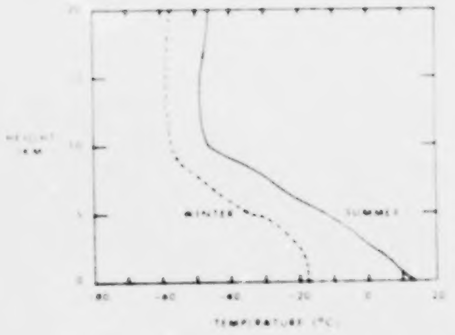
Variation with Height

In the lower region of the atmosphere extending from the surface to about 2 km., the temperature distribution varies considerably depending upon the character of the underlying surface and upon the radiation at the surface. The temperature may decrease with height or it may actually increase with height (inversion). This region is the lower troposphere and is the region of most interest in air pollution meteorology. The remainder of the troposphere has a decrease of temperature with height on the order of 4 to 8°C per km. The stratosphere is a region with isothermal or slight inversion lapse rates. The layer of transition between the troposphere and stratosphere is called the tropopause. The tropopause varies in height from about 8 to 20 km, and is highest near the equator, lowest near the poles. Figures 3 and 4 indicate typical temperature variations with height for two latitudes for summer and winter in the troposphere and lower stratosphere.



VARIATION OF TEMPERATURE WITH HEIGHT AT [illegible] NORTH LATITUDE

FIGURE 3



VARIATION OF TEMPERATURE WITH HEIGHT AT [illegible] NORTH LATITUDE

FIGURE 4

Above the stratosphere, the high atmosphere has several layers of differing characteristics. A rough indication of the variation of temperature with height including the high atmosphere is shown in Figure 5.

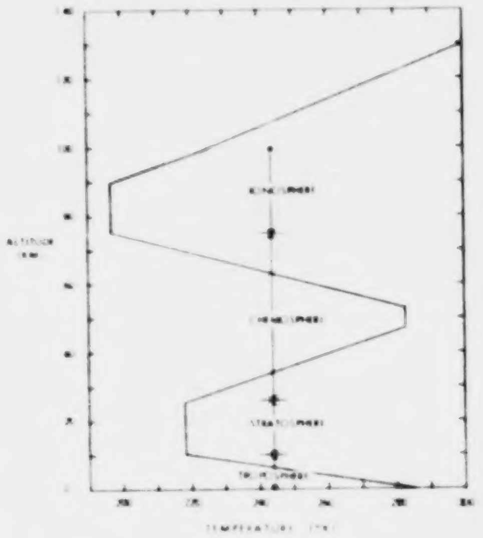


FIGURE 5

Horizontal Variation

Temperature also varies horizontally particularly with latitude, being colder near the poles and warmer near the equator. However the influence of continents and oceans have considerable effects on modifying temperatures. The continents have more extreme temperatures becoming warmer in summer and colder in winter, whereas the oceans maintain a more moderate temperature year-round.

STABILITY AND INSTABILITY

Whether the atmosphere has a tendency to enhance vertical motions or to damp out vertical motions is important to atmospheric processes which produce weather as well as to the effects upon air pollutants. The stability of the atmosphere is highly dependent upon the vertical distribution of temperature with height.

Adiabatic Lapse Rate

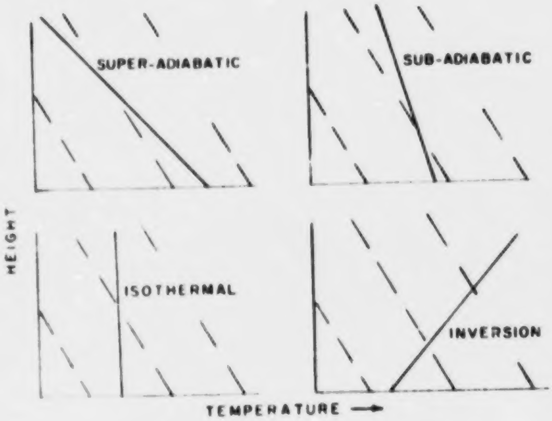
Due to the decrease of pressure with height, a parcel of air lifted to a higher altitude will encounter decreased pressure and will expand and in undergoing this expansion will cool. If this expansion takes place without loss or gain of heat to the parcel, the change is adiabatic. Similarly a parcel of air forced downward in the atmosphere will encounter higher pressures, will contract and will become warmer. This rate of cooling with lifting or heating with descent is the dry adiabatic process lapse rate and is 5.4°F per 1000 feet or approximately 1° C per 100 meters. This process lapse rate is the rate of heating or cooling of any descending or rising parcel of air in the atmosphere and should not be confused with the existing temperature variation with height at any one time, the environmental lapse rate.

Environmental or Prevailing Lapse Rate

The manner in which temperature changes with height at any one time is the prevailing lapse rate. This is principally a function of the temperature of the air and of the surface over which it is moving and the rate of exchange of heat between the two. For example, during clear days in midsummer the ground will be rapidly heated by solar radiation resulting in rapid heating of the layers of the atmosphere nearest the surface, but further aloft the atmosphere will remain relatively unchanged. At night radiation from the earth's surface cools the ground and the air adjacent to it, resulting in only slight decrease of temperature with height or if surface cooling is great enough, temperature will increase with height.

If the temperature decreases more rapidly with height than the dry adiabatic lapse rate, the air has a super-adiabatic or strong lapse rate and the air is unstable. If a parcel of air is forced upwards it will cool at the adiabatic lapse rate, but will still be warmer than the environmental air. Thus it will continue to rise. Similarly, a parcel which is forced downward will heat dry adiabatically but will remain cooler than the environment and will continue to sink.

For environmental lapse rates that decrease with height at a rate less than the dry adiabatic lapse rate (sub-adiabatic or weak lapse) a lifted parcel will be cooler than the environment and will sink; a descending parcel will be warmer than the environment and will rise. Figure 6 shows the relative relation between the environmental lapse rates of super-adiabatic (strong lapse), sub-adiabatic (weak lapse), isothermal, and inversion with the dry adiabatic process lapse rate as dashed lines.



Types of Temperature Structure with Height Related to the Dry Adiabatic Process Lapse Rate

FIGURE 6

Lifting motions which will cause cooling at dry adiabatic lapse rates may be due to upslope motion over mountains or rising over a colder air mass. Descending motion (subsidence) may occur to compensate for the lateral spreading of air in high pressure areas.

WATER IN THE ATMOSPHERE

In the section on radiation the importance of water vapor on the balance of incoming and outgoing radiation was shown. The temperature of the atmosphere is below the boiling point of water, yet water is volatile enough to evaporate (change from liquid to gas) or sublimate (change from solid to gas) at atmospheric temperatures and pressures. Condensation or crystallization of water vapor in the atmosphere as clouds and on the ground as dew or frost is commonplace. Certainly, water in the form of clouds, fog, and precipitation are familiar elements of weather and the latter one necessary for agriculture and supplies of ground water.

One measure of the amount of moisture in the air is the dew point which is the temperature at which saturation is reached if the air is cooled at a constant pressure without addition or loss of moisture. In the atmosphere, saturation frequently occurs due to the adiabatic cooling of lifted air parcels until the dew point for the lower pressure is reached. Further cooling will condense water vapor releasing the heat of condensation and because of this release of heat, cooling of ascending saturated air does not occur at the dry adiabatic lapse rate but at the pseudo-adiabatic lapse rate which is a smaller temperature decrease with height.

WINDS

Wind is nothing more than air in motion and although it is a motion in three dimensions, usually only the horizontal component is considered in terms of direction and speed. In the free atmosphere (above the effects of the earth's friction) two forces are important, the first, the Coriolis force, is due to the tendency for the air to move in a straight path while the earth rotates underneath. The Coriolis force is at right angles to the wind velocity, to the right in the northern hemisphere and to the left in the southern hemisphere, is proportional to the wind velocity, and decreases with latitude. The other force is the pressure gradient force, with direction from high to low pressure. Above the friction layer, in regions where the lines of constant pressure (isobars) are straight and the latitude is greater than 20°, the two forces are in balance (See Figure 7) and the wind blows parallel to the isobars with low pressure to the left. For curved isobars the forces are not in balance, their resultant producing a centripetal acceleration. In the lowest portion of the atmosphere frictional drag (not due to molecular friction but to eddy viscosity) slows down the wind speed and since the Coriolis force is proportional to the wind speed reduces the Coriolis force. The balance of forces under Frictional flow is shown in Figure 8. It will be noted that under frictional flow the wind has a component across the isobars toward lower pressure.

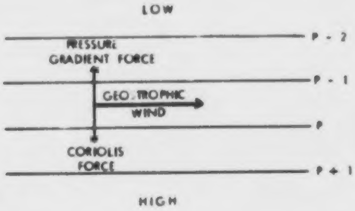


FIGURE 7

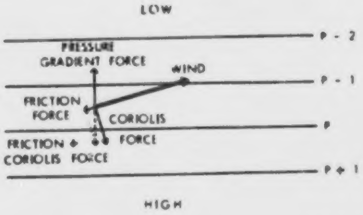


FIGURE 8

ANTICYCLONES AND CYCLONES

Migrating areas of high pressure (anticyclones) and low pressure (cyclones) and the fronts associated with the latter are responsible for the day to day changes in weather that occur over most of the mid-latitude regions of the earth. The low pressure systems in the atmospheric circulation are related to perturbations along the jet stream (the region of strongest horizontal temperature gradient in the upper troposphere and consequently the region of strongest winds) and form along frontal surfaces separating masses of air having different temperature and moisture characteristics. The formation of a low pressure system is accompanied by the formation of a wave on the front consisting of a warm front and a cold front both moving around the low in a counterclockwise sense. The life cycle of a typical cyclone is shown in Figure 9. The cold front is a transition zone between warm and cold air where the cold air is moving in over the area previously occupied by warm air. Cold fronts generally have slopes from 1/50 to 1/150. Warm fronts separate advancing warm air from retreating cold air and have slopes on the order of 1/100 to 1/300 due to the effects of friction on the trailing edge of the front. Figure 10 illustrates a vertical cross section though both a warm and a cold front.

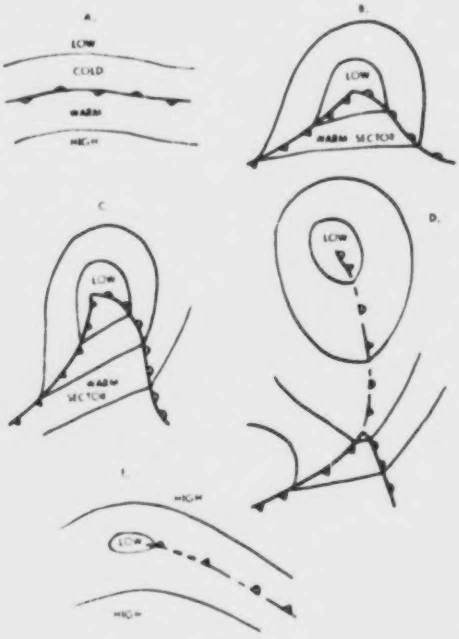
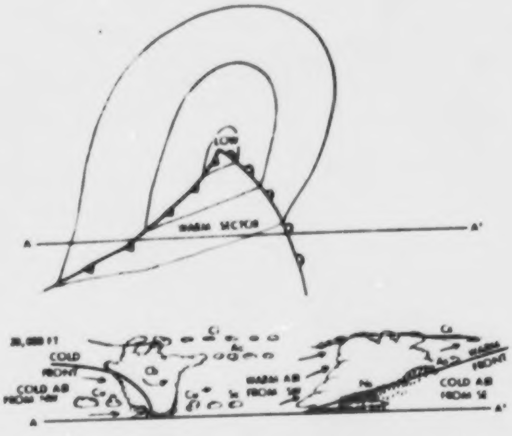


FIGURE 9



CROSS SECTION THROUGH A COLD FRONT AND A WARM FRONT

FIGURE 10

AIR MASSES

Air masses are frequently divided by frontal systems and are usually classified according to the source region of their recent history. Air masses are classified as maritime or continental according to origin over the ocean or land, and arctic, polar, or tropical depending principally on the latitude of origin. Air masses are modified by vertical motions and by the effects of radiation upon the surfaces over which they move.

CONDENSATION, CLOUDS, AND PRECIPITATION

Condensation of water vapor upon suitable condensation nuclei in the atmosphere causes clouds. Large hygroscopic nuclei will condense water vapor upon them even before saturation is reached. Table 2 indicates the relative sizes of different particles. At below freezing temperatures supercooled water frequently exists for few nuclei act as crystallization nuclei. Of course, only a small proportion of all clouds produce rain. It is necessary that the droplets increase in size both so that they will have appreciable fall velocity and also so that complete evaporation of the drop will not occur before it reaches the ground. Table 3 indicates the distance of fall for different size drops before evaporation occurs. Growth of condensation drops into drops large enough to fall is thought to originate with the large condensation nuclei which grow larger as they drop through the cloud. The presence of an electric field in clouds generally helps the growth into raindrops.

TABLE 2

Sizes of Particles

Particles	Size (microns)
Small ions	less than 10^{-3}
Medium ions	10^{-3} to 5×10^{-2}
Large ions	5×10^{-2} to 2×10^{-1}
Aitken nuclei	5×10^{-2} to 2×10^{-1}
Smoke, haze, dust	10^{-1} to 2
Large condensation nuclei	2×10^{-1} to 10
Giant condensation nuclei	10 to 30
Cloud or fog droplets	1 to 100
Drizzle drops	100 to 500
Raindrops	500 to 4000

TABLE 3

Distance of Fall Before Evaporation (from Findeisen)

Radius (microns)	Distance of Fall
1	3.3 10^{-4} cm.
10	3.3 cm.
100	150 m.
1000	42 km.
2500	280 km.

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ADIABATIC DIAGRAM

D. B. Turner*

The adiabatic diagram can be used to plot the distribution of temperature, and moisture with height in the atmosphere. This is of considerable use to the meteorologist in determining freezing levels, condensation levels of moisture in lifted air parcels, forecasting cloud bases and tops, determining stability for cloud formation and thunderstorm forecasting. To the air pollution meteorologist a sounding plotted on an adiabatic chart is principally useful to determine the large scale stability of the atmosphere over a given location. The principal source of atmospheric measurements that may be plotted on the adiabatic chart are the radiosonde measurements taken twice daily: 0000 GCT (1900 EST) and 1200 GCT (0700 EST) at about 66 stations in the contiguous United States. The method of obtaining these soundings is to release into the atmosphere a balloon borne instrument package having sensors for temperature, pressure, and humidity and a radio transmitter for relaying this information to the ground station. This information on the upper air is collected primarily to serve the purpose of forecasting and aviation briefing. Consequently, the information is not as detailed in the lowest 5000 feet as an air pollution meteorologist desires. Also, in air pollution meteorology, it is desirable to have information more frequently than 12 hours apart. In spite of these deficiencies for air pollution purposes, the soundings from the radiosonde network will give indications of the stability of the atmosphere.

The adiabatic chart used by the Weather Bureau (Chart D-II) is shown at the end of this section. Temperature on a linear scale is plotted against pressure on a logarithmic scale. The different lines are explained in the legend in the upper right. The important lines for air pollution purposes in addition to the pressure and temperature lines are the dry adiabats, the solid green lines running diagonally from lower right to upper left.

A temperature sounding may be plotted by locating each significant level reported by the temperature and pressure given for that level. The plotted points may then be connected by straight lines. This gives the temperature sounding. The dew point curve may also be plotted giving a measure of humidity.

The stability of a portion of the sounding may be compared with the dry adiabatic lapse rate and with the isotherms. If the temperature decreases more rapidly than the dry adiabats through a layer, this layer is super adiabatic and quite unstable. If the temperature decreases, but at a rate less than the dry adiabatic lapse rate, the layer is sub-adiabatic and is more stable than super adiabatic. A sub-adiabatic layer may be relatively unstable or stable depending upon the humidity structure in the layer. If the temperature increases with height, the layer is an inversion. Inversions are stable layers.

Inversions that form based at ground level are generally radiation inversions caused by the cooling of the earth's surface and the adjacent air. However, there may also be advection inversions formed by the air's passage over a relatively cold surface. These two types of surface based inversion generally cannot be distinguished by inspection of the sounding plotted on an adiabatic diagram. A surface based inversion on an afternoon sounding is more apt to be an advection inversion.

There are two general classifications of inversions with bases above the ground: frontal inversions and subsidence inversions. Both of these can be ground based inversions as well as found aloft.

Frontal inversions are discontinuities in the temperature profile due to the transition between the cold air below and the warm air aloft. Frontal inversions usually are accompanied by increase in moisture through

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the inversion. Subsidence inversions are caused by the sinking motion above high pressure areas and generally have rapidly decreasing humidities above the base of the inversion.

Surveys of the meteorological aspects of air pollution are often concerned with the extent of horizontal and vertical mixing. A quantity referred to as the mixing depth is quite useful when considering dilution of pollutants in the vertical. The usual method of estimating mixing depths is to consider the stability as portrayed on a temperature sounding remembering that unstable lapse rates favor vertical mixing and stable lapse rates restrict vertical motion. The mixing depth is generally the height above the ground to which a super or dry adiabatic lapse rate is maintained. Thus, the maximum mixing depth is frequently determined where the dry adiabat drawn through the maximum temperature for the day intersects the sounding on an adiabatic diagram.

In the figures are some soundings representative of different types of conditions in the atmosphere. Figure 1 is the temperature sounding for 12 GCT (0700 EST) for Dayton, Ohio on a clear day in summer. There is a radiation inversion based at the surface. The sounding 12 hours later (Figure 2) shows that the surface inversion has been eliminated and that nearly dry adiabatic conditions exist from the surface to 800 mb (2068 meters).

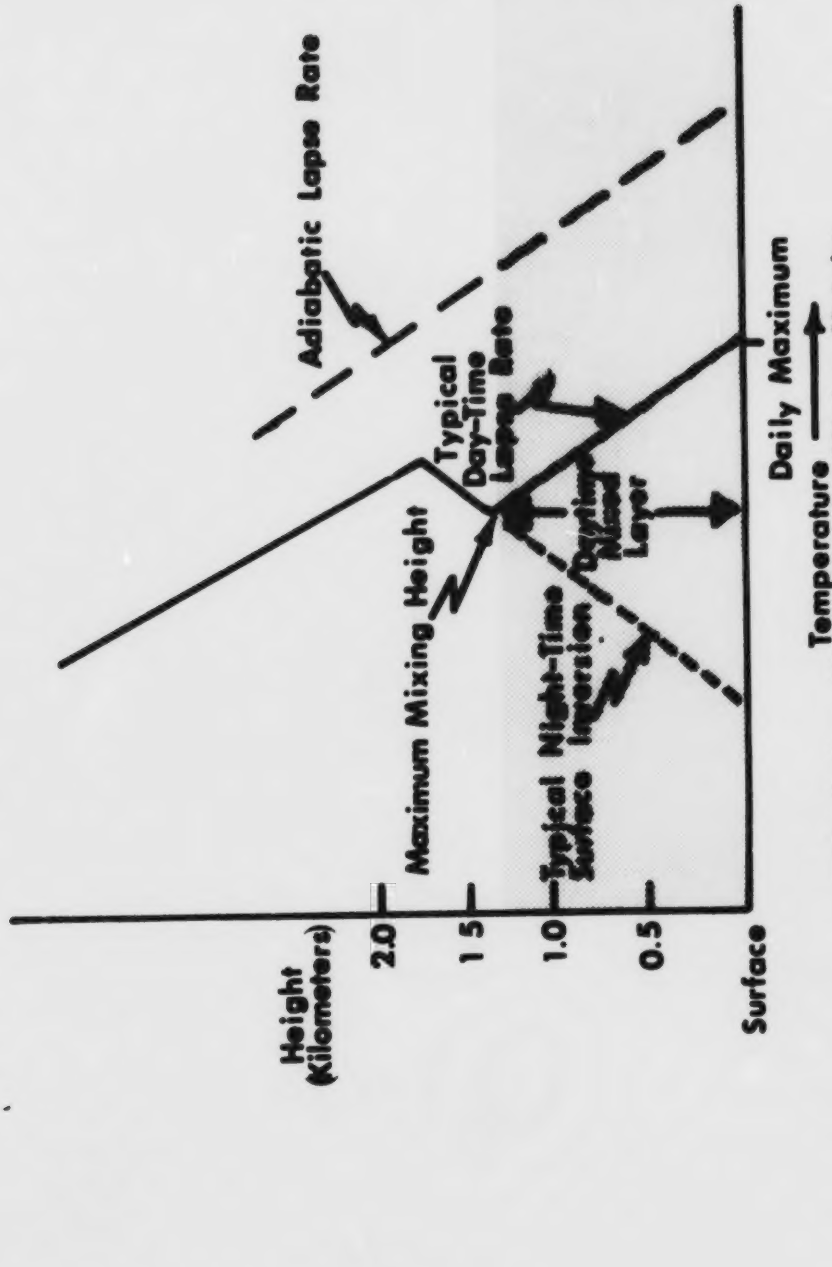
Figure 3 (5 days later than Figure 1) is representative of a cloudy summer period. Sub-adiabatic conditions occur on the morning sounding and dry adiabatic (through 1870 meters) conditions occur on the evening sounding (Figure 4).

Figures 5 and 6 are for Los Angeles for a day with no smog. On the morning sounding (12 GCT, 0400 PST) sub-adiabatic conditions occur from the surface to about 1000 meters with the marine inversion layer about 200 meters thick above this. On the afternoon sounding (Figure 6) strong lapse (super adiabatic) conditions occur through a shallow surface layer with sub-adiabatic conditions extending to almost 1500 meters. The winds beneath the inversion range from 5 to 15 knots.

Figures 7 and 8 for Los Angeles are for a smog day just 4 days before Figures 5 and 6. The morning sounding (0400 PST) indicates sub-adiabatic conditions through less than 300 meters with a strong inversion above. The afternoon sounding (Figure 8) shows super adiabatic conditions from the surface to the inversion base about 300 meters above the surface. Winds beneath the inversion are less than 5 knots during the morning and are about 15 knots during the afternoon.

Figures 9 and 10 are for Dayton, Ohio during an air pollution potential alert for the Northeast U. S. and Ohio Valley. On the morning sounding (0700 EST) Figure 9 an inversion extends from the surface to 940 millibars (about 400 meters). In spite of clear skies causing temperatures to reach about 60°F, this was insufficient to break the inversion. The surface based radiation inversion is reforming by 1900 EST (Figure 10).

It is estimated that the maximum mixing height achieved during this day was about 350-400 meters, (the height where the dry adiabat through 15.5°C (60°F) intersects the 00 GCT sounding).


Height (Kilometers)
2.0
1.5
1.0
0.5
Surface
Maximum Mixing Height
Typical Surface Night-Time Inversion
Daytime Mixed Layer
Typical Day-Time Lapse Rate
Adiabatic Lapse Rate
Daily Maximum
Temperature →

Calculation Of Maximum Mixing Height

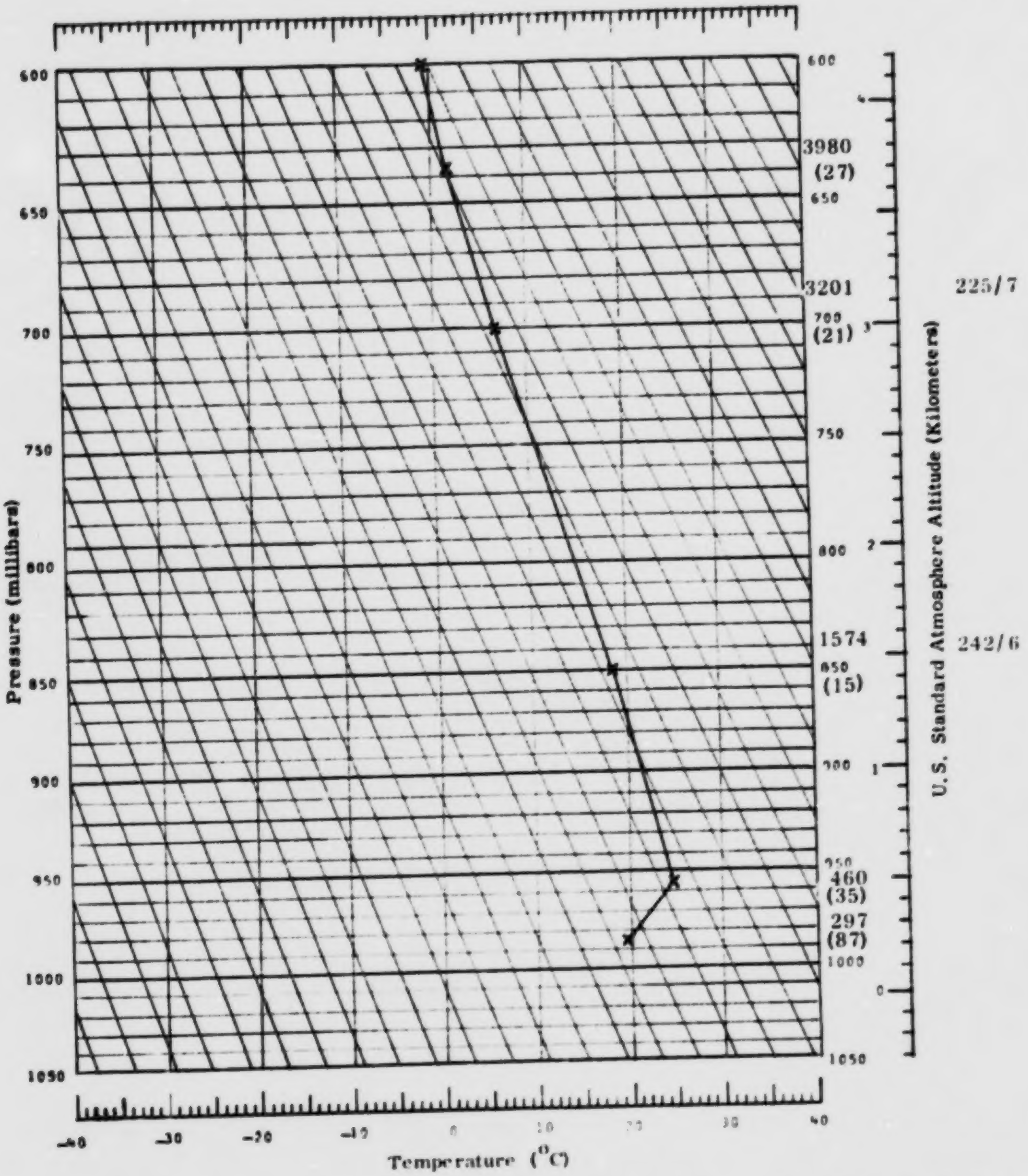


Figure 1 - Temperature Sounding For a Relatively Clear Day, Dayton, Ohio 1 July 1961, 1200 GCT (0700 EST).

Heights in meters are given for each level at the right hand margin. Figures in parenthesis are relative humidities in percent. Winds in degrees and meters per second are given at the extreme right.

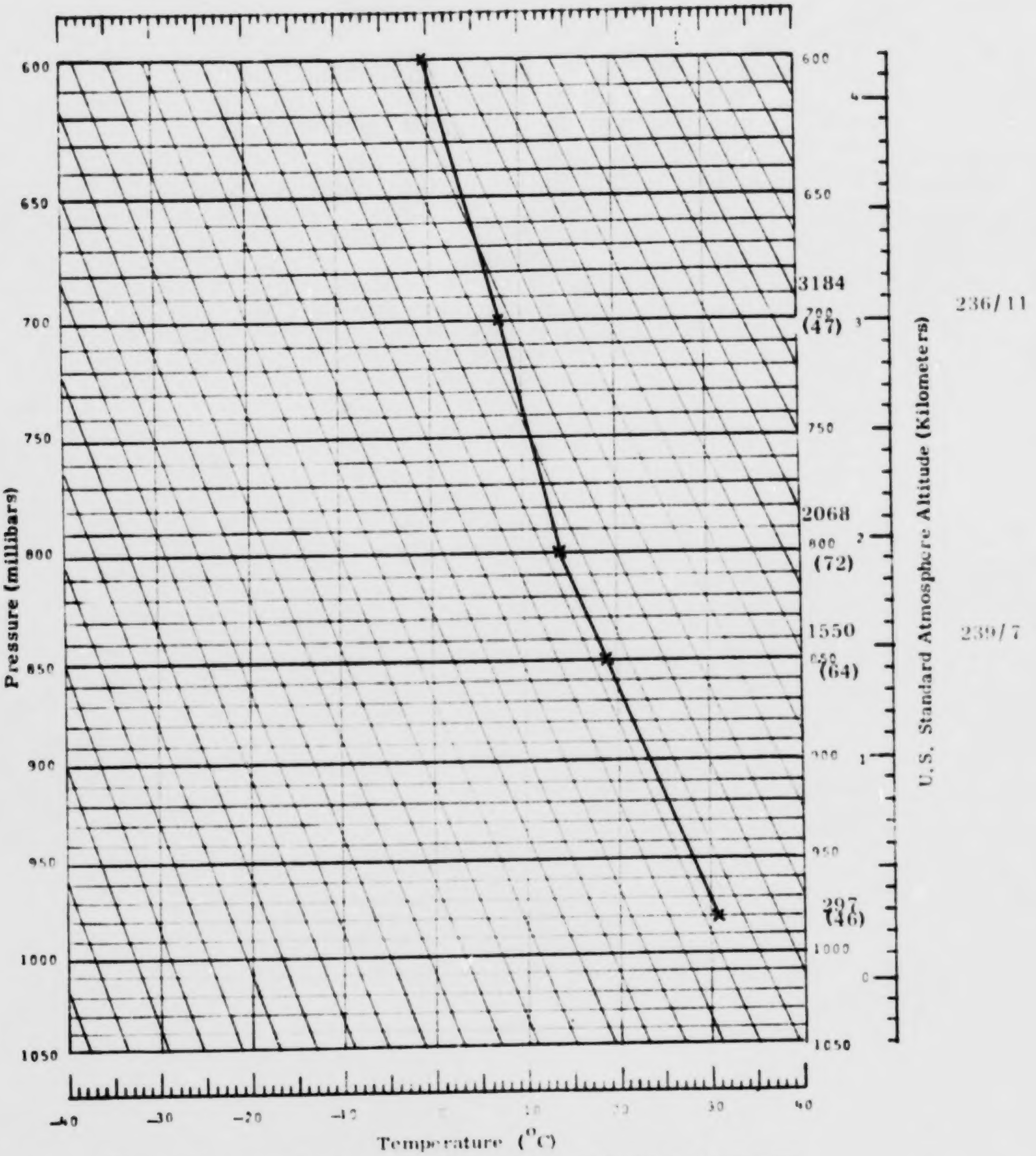


Figure 2- Temperature Sounding For a Relatively Clear Day Dayton, Ohio, 2 July 1961, 0000 GCT, (1900 EST 1 July).

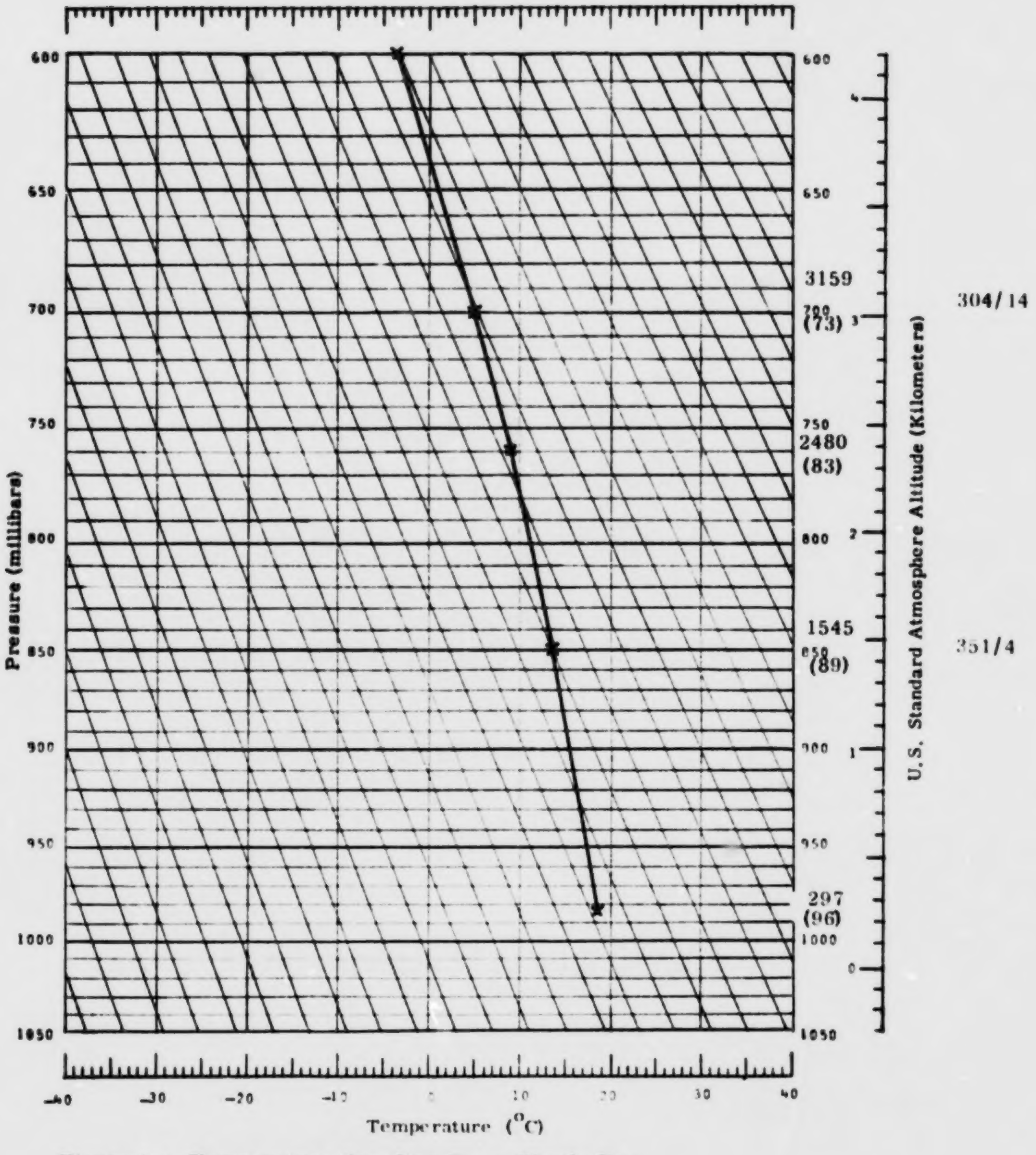


Figure 3 - Temperature Sounding For a Cloudy Day, Dayton, Ohio, 6 July 1961, 1200 GCT (0700 EST).

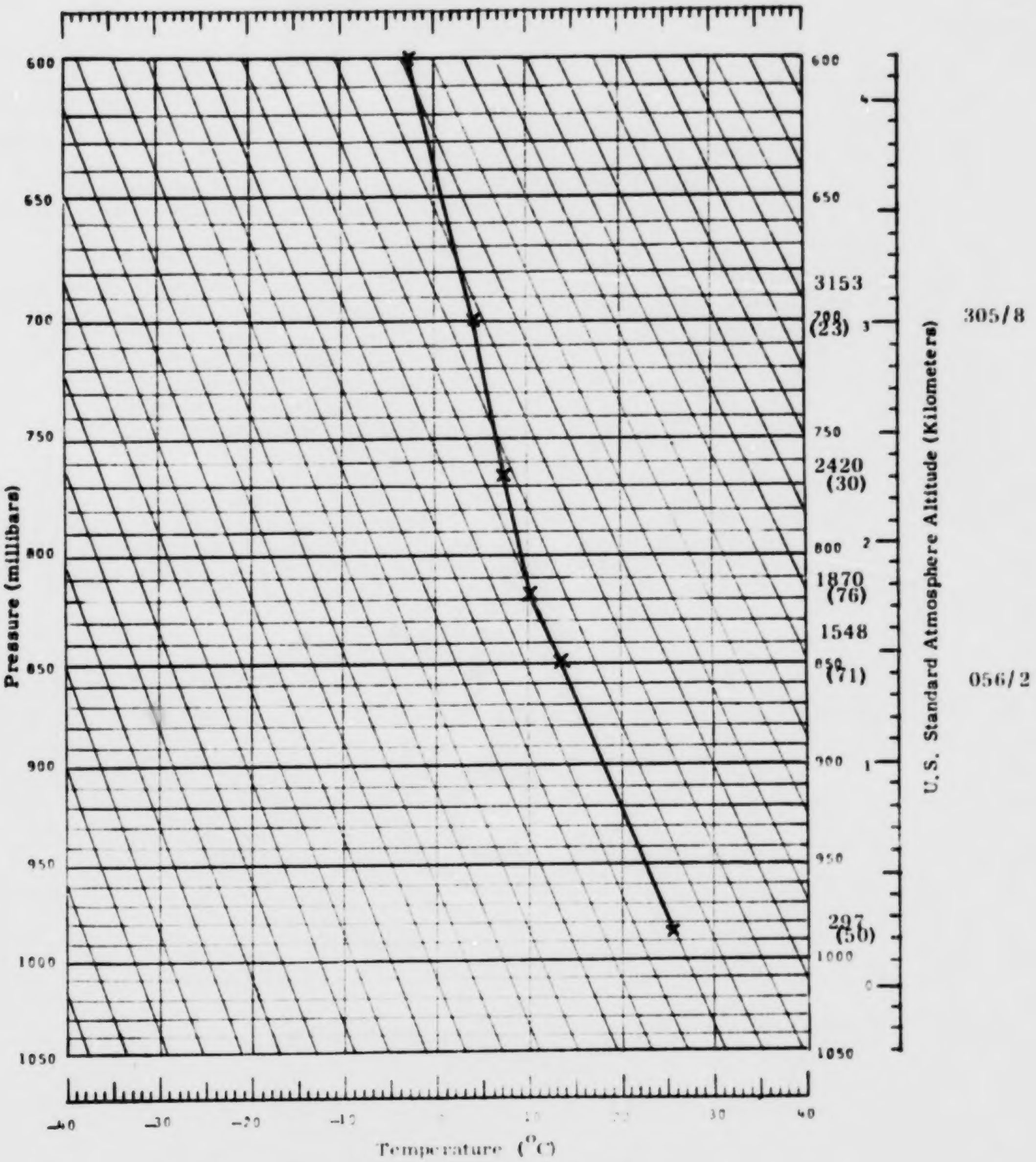
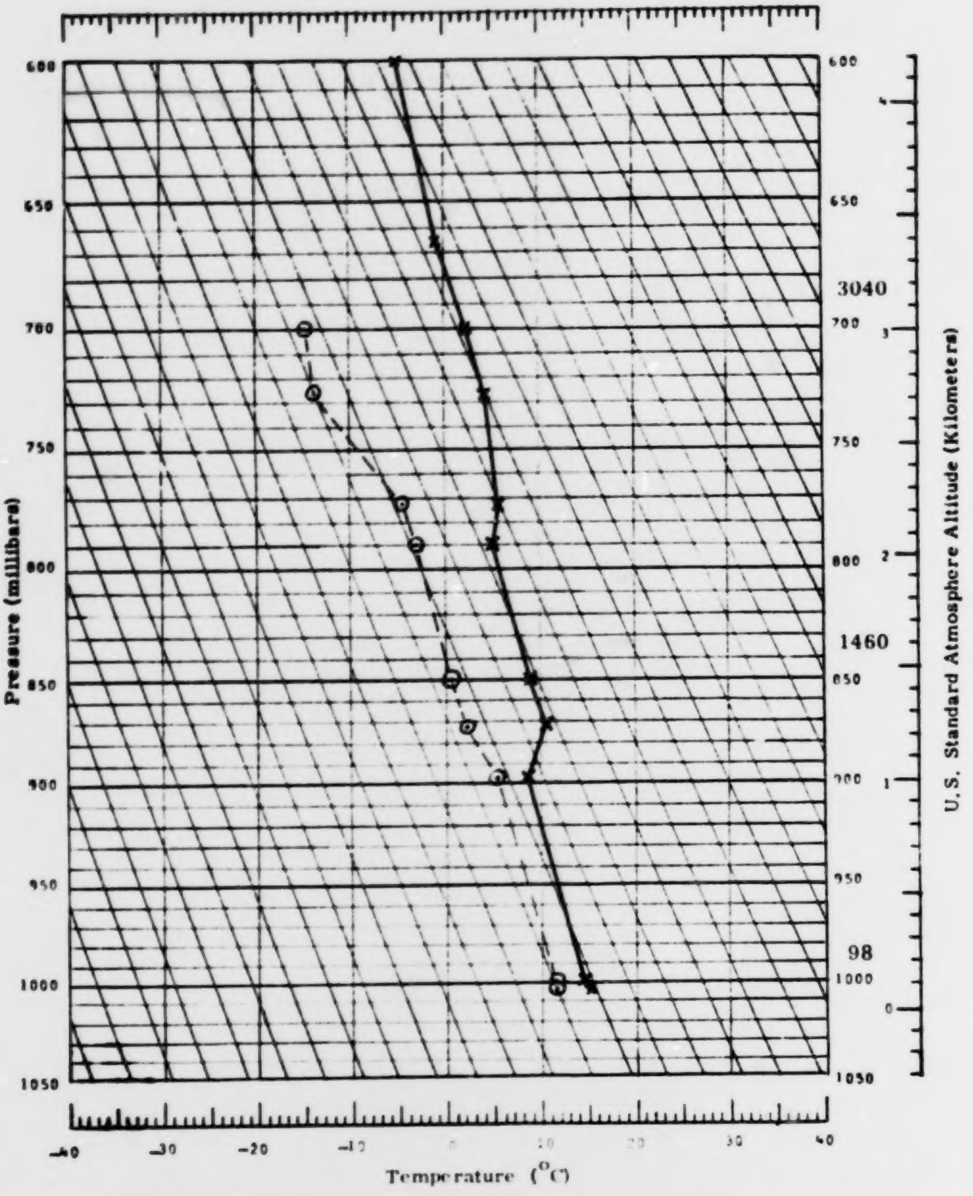


Figure 4 - Temperature Sounding For a Cloudy Day, Dayton, Ohio, 7 July 1961, 0000 GCT, (1900 EST 6 July).



010/3

330/2

110/7

Figure 5- Temperature Sounding For a Day Free of Smog, Los Angeles, 5 October 1962, 1200 GCT. (0400 PST).

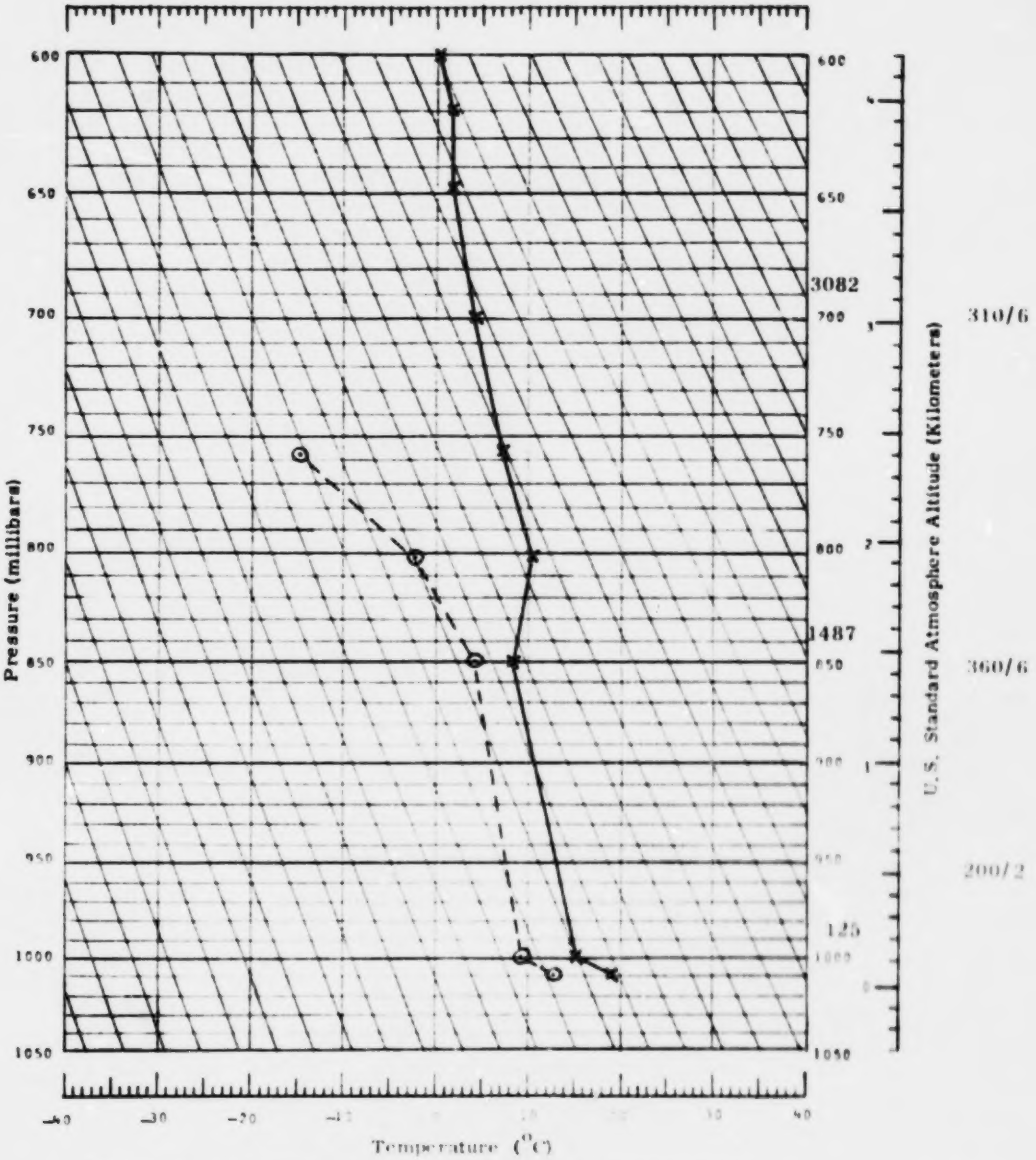


Figure 6- Temperature Sounding For a Day Free of Smog, Los Angeles, 6 October 1962, 0000 GCT (1600 PST, 5 October).

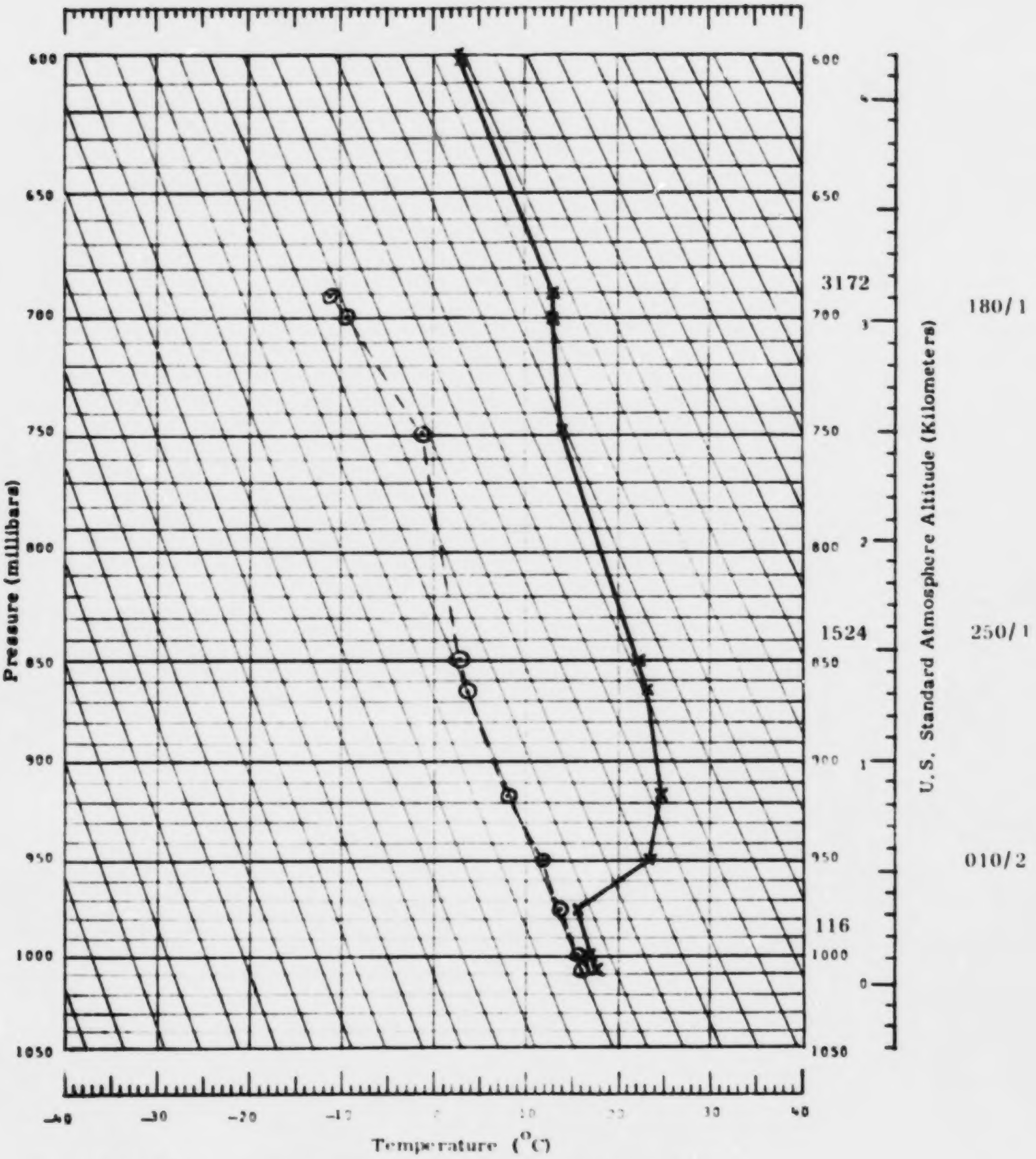


Figure 7- Temperature Sounding For a Day With Smog, Los Angeles, 1 October 1962, 1200 GCT, (0400 PST).

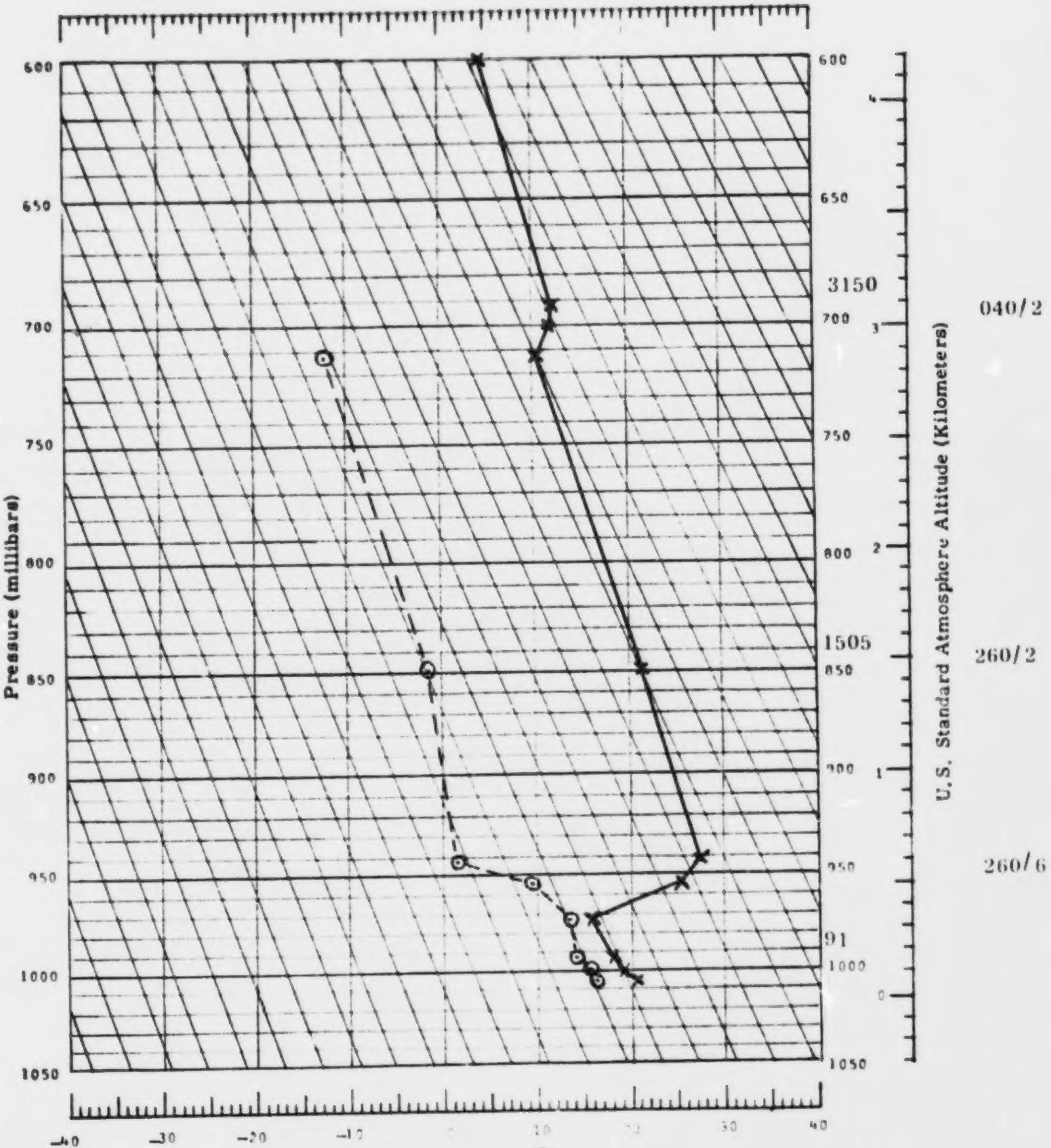


Figure 8- Temperature Sounding For a Day With Smog, Los Angeles, 2 October 1962, 0000 GCT (1600 PST, 1 October).

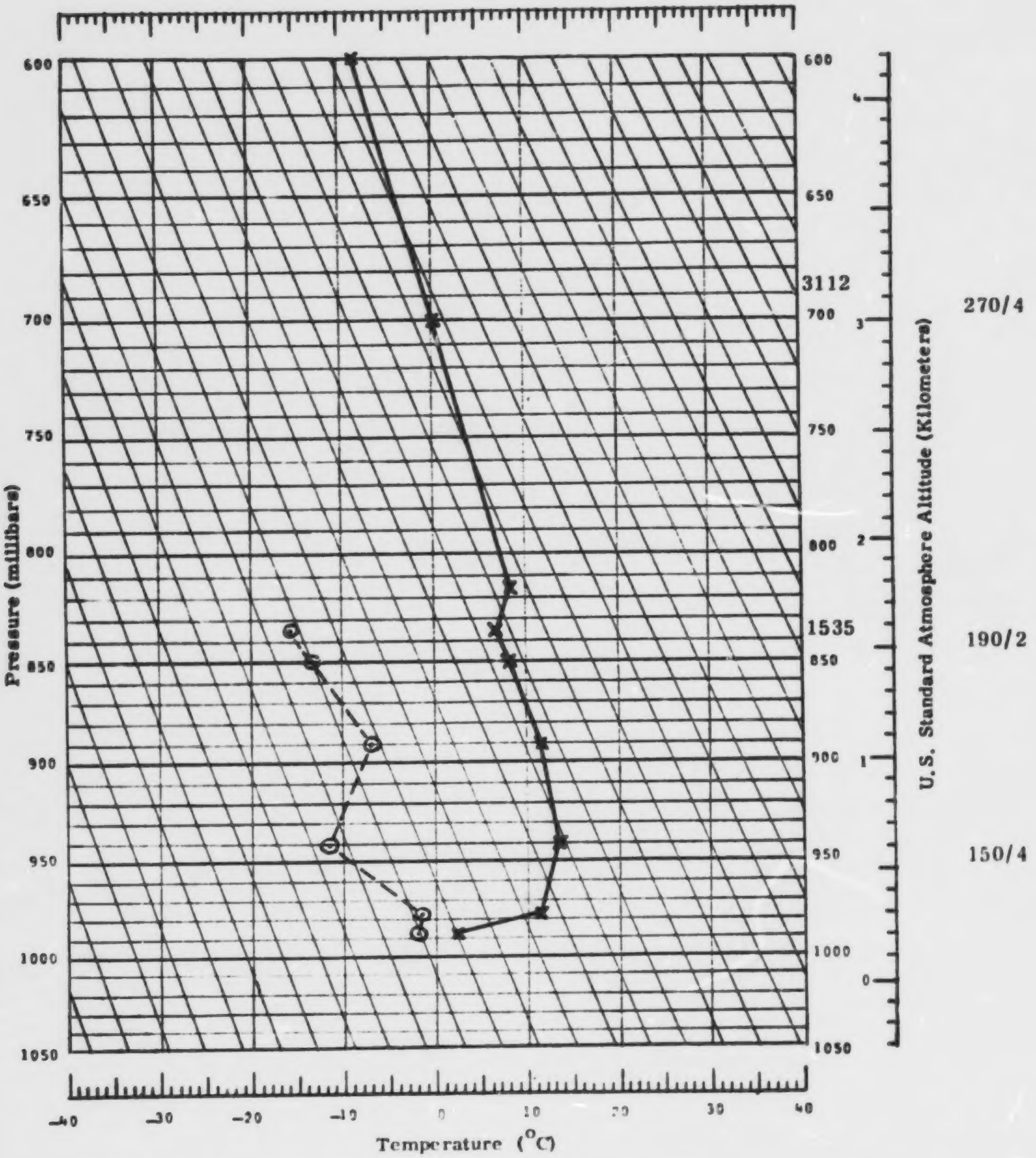


Figure 9- Temperature Sounding During an Air Pollution Potential Alert, Dayton, Ohio, 3 December 1962, 1200 GCT, (0700 EST).

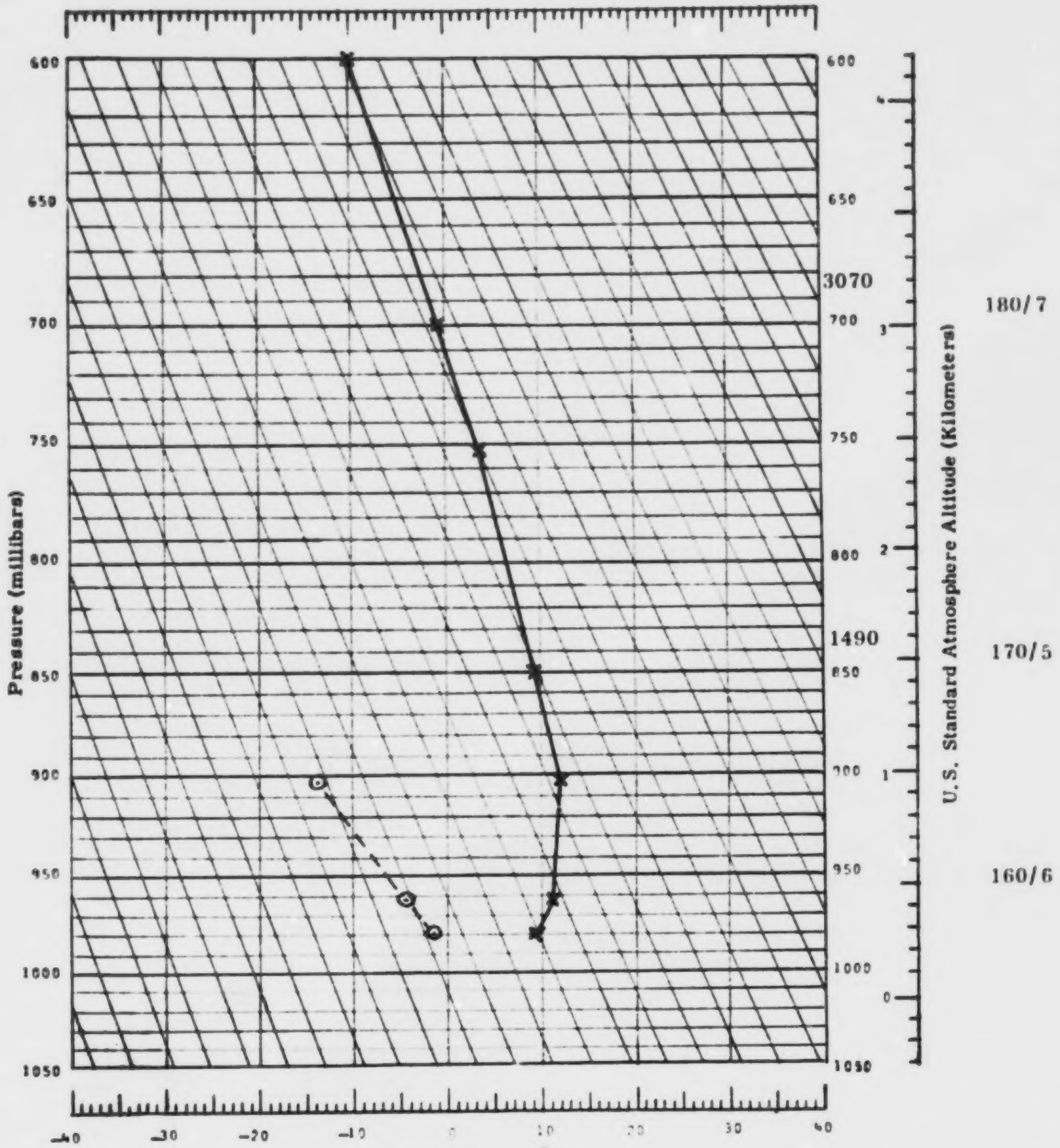


Figure 10 - Temperature Sounding During An Air Pollution Potential Alert, Dayton, Ohio, 4 December 1962, 0000 GCT, (1900 EST, 3 December).

SECTION TWO

AIR POLLUTION METEOROLOGY

Effects of Meteorological Parameters on Transport and Diffusion
Pollutant Concentration Variation
Influence of Topography on Transport and Diffusion
Equation of State and Conversion of Concentrations
Meteorological Roses

EFFECTS OF METEOROLOGIC PARAMETERS ON TRANSPORT AND DIFFUSION

D. B. Turner*

The air pollution cycle can be considered to consist of three phases: the release of air pollutants at the source, the transport and diffusion in the atmosphere, and the reception of air pollutants in reduced concentrations by people, plants, animals, or inanimate objects. The influence of meteorology is to the greatest extent during the diffusion and transport phase. The motions of the atmosphere which may be highly variable in four dimensions are responsible for the transport and diffusion of air pollutants.

Although the distribution with time of a cloud of pollutant material will depend on the summation of all motions of all sizes and periods acting upon the cloud, it is convenient to first consider some mean atmospheric motions over periods on the order of an hour.

WIND DIRECTION

What effect will the mean wind direction have on an air pollutant? If the wind direction is representative of the height at which the pollutant is released, the mean direction will be indicative of the direction of travel of the pollutants. In meteorology it is conventional to consider the wind direction as the direction from which the wind blows, therefore a north-west wind will move pollutants to the south-east of the source.

WIND SPEED

The effect of wind speed is two-fold. The wind speed will determine the travel time from a source to a given receptor, e. g. if a receptor is located 1000 meters downwind from a source and the windspeed is 5 meters /second, it will take 260 seconds for the pollutants to travel from the source to the receptor. The other effect of wind speed is a dilution in the downwind direction. If a continuous source is emitting a certain pollutant at the rate of 10 grams/second and the wind speed is 1 meter/second then in a downwind length of the plume of 1 meter will be contained 10 grams of pollutant since 1 meter of air moves past the source each second. Next, consider that the conditions of emission are the same but the wind speed is 5 meters/second. In this case since 5 meters of air moves past the source each second, each meter of plume length contains 2 grams of pollutant. Therefore it can be seen that the dilution of air pollutants released from a source is proportional to the wind speed. This may be restated in another form: The concentration of air pollutants is inversely proportional to wind speed.

VARIABILITY OF THE WIND

In the preceding paragraphs consideration of only the mean speed and direction of wind has been made. Of course, there are deviations from this mean velocity. There are velocity components in all directions so that there are vertical motions as well as horizontal ones. These random motions of widely different scales and periods are essentially responsible for the movement and diffusion of pollutants about the mean downwind path. These motions can be considered atmospheric turbulence. If the scale of a turbulent motion i. e. the size of an eddy, is larger than the size of the pollutant plume in its vicinity, the eddy will move that portion of the plume. If an eddy is smaller than the plume its effect will be to diffuse or spread out the plume. This diffusion caused by the eddy motion is widely variable in the atmosphere but even when this diffusion is least, it is on the order of three orders of magnitude greater than the diffusion by molecular action alone.

MECHANICAL TURBULENCE

Mechanical turbulence is the induced eddy structure of the atmosphere due to the roughness of the surface over which the air is passing. Therefore the existance of trees, shrubs, buildings, and terrain features will

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cause mechanical turbulence. The height and spacing of the elements causing the roughness will affect the turbulence. In general, the higher the roughness elements the greater the mechanical turbulence. In addition the mechanical turbulence increases as wind speed increases.

THERMAL TURBULENCE

Thermal turbulence is that induced by the stability of the atmosphere. When the earth's surface is heated by the sun's radiation, the lower layer of the atmosphere becomes unstable and thermal turbulence becomes greater, expecially under conditions of light wind. On clear nights with light winds, heat is radiated from the earth's surface resulting in cooling of the ground and air adjacent to it. This results in extreme stability of the atmosphere near the earth's surface. Under these conditions turbulence is at a minimum.

RELATION OF TURBULENCE TO WIND RECORDS

Attempts to relate different measures of turbulence of the wind to atmospheric diffusion have been made for quite some time. Lowry (1951) related the distance of the maximum concentration to the standard deviation of wind direction over 10 to 15 minute periods. Smith (1951) has used a classification of wind trace types using wind vane records as an indication of atmospheric stability. Hay and Pasquill (1957, 1959), Cramer (1958), and Islitzer (1961) have all compared diffusion experiment results with statistics of wind direction fluctuations in both the horizontal and vertical. Direct methods of relating wind statistics to estimates of dispersion (Pasquill, 1961, 1962) show promise and attempts at developing suitable instrumentation to yield the necessary wind statistics directly have been made (Jones and Pasquill, 1959).

RELATION OF TURBULENCE TO ATMOSPHERIC STABILITY

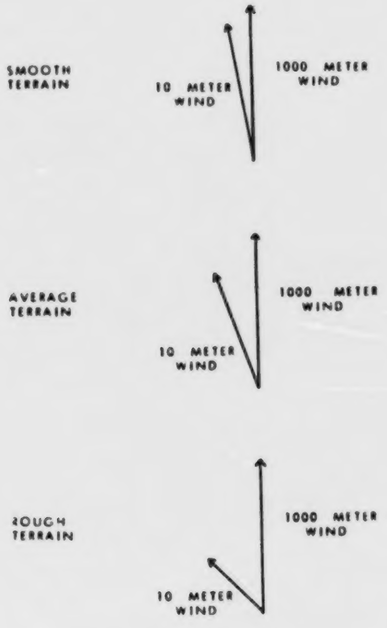
Relations of a more qualitative type have been noted between atmospheric diffusion and the stability of the atmosphere. Measurement of atmospheric stability by temperature difference measurements on a tower are frequently utilized as an indirect measure of turbulence, particularly where climatological estimates of turbulence are desired. Under strong lapse or super-adiabatic conditions of temperature change with height, strong vertical and horizontal mixing takes place in the atmosphere contrasted to inversion conditions with slight horizontal mixing but extremely limited vertical mixing. (See the section on The Influence of Vertical Temperature Structure Upon Stack Effluents)

VARIATIONS OF WIND SPEED AND DIRECTION WITH HEIGHT

Wind speed is generally found to increase with height above the ground and wind direction to veer (turn clockwise) with height (in the northern hemisphere at extratropical latitudes) due to the effects of friction with the earth's surface. The amount of these increases in speed and veering in direction are widely variable and to a great degree related to the roughness of the surface and the stability of the atmosphere.

EFFECT OF SURFACE ROUGHNESS

Consider the surface wind as measured at 10 meters compared to the wind above the influence of the earth's friction, for example about 1000 meters. Over smooth terrain such as the great plains or over the ocean the speed at the surface is on the order of 0.9 the upper wind and the degree of veering with height on the order of 10°. (See Figure 1). Over average terrain with small changes in elevation and with some trees and shrubs, the surface speed is more like 4/5 of the upper wind and the amount of veering with height about 15° to 20°. Over rough terrain, quite hilly or mountaneous or with numerous buildings and vegetation, the surface speed may be only half the speed of the upper wind and the amount of veering with height as much as 40° to 45°.



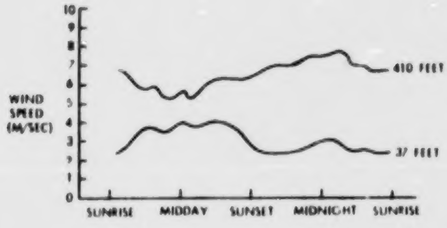
EFFECT OF ROUGHNESS ON VARIATION OF WIND WITH HEIGHT

FIGURE 1

DIURNAL VARIATION

During the daytime, solar heating causes turbulence to be at a maximum and vertical motions to be strongest. This causes the maximum amount of momentum exchange between various levels in the atmosphere. Because of this, the variation of wind speed with height is least during the daytime. Also the amount of veering with height is least (on the order of 15° to 20° over average terrain). The thickness of the friction layer will also be greatest during the day due to the vertical exchange.

At night the vertical motions are least and the effect of friction is not felt through as deep as a layer as during the day. The surface speed over average terrain is much less than the free atmosphere wind (on the order of 1/4 to 1/3 that of the 1000 meter wind) and the amount of veering with height may be on the order of 40° to 45°. Figure 2 shows the diurnal variation of wind speed at two different levels on a meteorological tower (Singer and Raynor, 1957).



DIURNAL VARIATION OF WIND SPEED

Data from Meteorological Tower
Brookhaven National Laboratory
April 1950-March 1952

FIGURE 2

FRONTAL TRAPPING

Since frontal systems are accompanied by inversions, trapping of air pollution beneath these inversions can occur. These may allow relatively high concentrations. Frontal trapping may occur with either warm fronts or cold fronts. Since warm fronts are usually slower moving and also the frontal surface slopes more gradually than that of a cold front, trapping will generally be more important with warm fronts. In addition the low level and surface wind speeds ahead of a warm front - within the trapped sector - will usually be lower than the wind speeds behind a cold front. Because of the orientation of frontal systems with respect to low pressure systems in the Northern hemisphere, most surface winds associated with cold fronts are from the quadrant west through north and winds associated with warm fronts are from the east through south quadrant. Therefore most warm frontal trapping will occur to the west through north from a given source and cold frontal trapping to the east through south of the source.

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POLLUTANT CONCENTRATION VARIATION

D. B. Turner*

THE INFLUENCE OF VERTICAL TEMPERATURE STRUCTURE UPON STACK EFFLUENTS

The manner in which stack effluents diffuse is primarily a function of the stability of the atmosphere. Church (1949) has typed the behavior of smoke plumes into five classes. Hewson (1960) has added a sixth class taking into account inversions aloft

LOOPING

Looping occurs with a superadiabatic lapse rate. Large thermal eddies are developed in the unstable air and high concentrations may be brought to the ground for short time intervals. Diffusion is good however when considering longer time periods. The superadiabatic conditions causing looping occurs only with light winds and strong solar heating. Cloudiness or high winds will prevent such unstable conditions from forming.

CONING

With vertical temperature gradient between dry adiabatic and isothermal,slight instability occurs with both horizontal and vertical mixing but not as intense as in the looping situation. The plume tends to be cone shaped hence the name. The plume reaches the ground at greater distances than with looping. Coning is prevalent on cloudy or windy days or nights. Diffusion equations are more successful in calculating concentrations for this type of plume than for any other.

FANNING

If the temperature increases upward the air is stable and vertical turbulence is suppressed. Horizontal mixing is not as great as in coning but still occurs. The plume will therefore spread horizontally but little if any vertically. Since the winds are usually light the plume will also meander in the horizontal. Plume concentrations are high but little effluent from elevated sources reaches the ground with this situation except when the inversion is broken due to surface heating, or terrain at the elevation of the plume is encountered. Clear skies with light winds during the night are favorable conditions for fanning.

LOFTING

Lofting occurs when there is a superadiabatic layer above a surface inversion. Under this condition diffusion is rapid upward but downward diffusion does not penetrate the inversion and so is damped out. With these conditions gases will not reach the surface but particles with appreciable settling velocities will drop through the inversion. Near sunset on a clear evening in open country is most favorable for lofting. Lofting is generally a transition situation and as the inversion deepens is replaced by fanning.

FUMIGATION

As solar heating increases the lower layers are heated and a super-adiabatic lapse rate occurs through a deeper and deeper layer. When the layer is deep enough to reach the fanning plume, thermal turbulence will bring high concentrations to the ground along the full length of the plume. This is favored by clear skies and light winds and is apt to occur more frequently in summer due to increased heating.

Another type of fumigation may occur in the early evening over cities. Heat sources and mechanical turbulence due to surface roughness causes a lapse condition in the lower layers of the stable air moving into the city from non-urban areas where radiation inversions are already forming. This causes a fumigation until the city loses enough heat so that the lapse condition can no longer be maintained.

TRAPPING

When an inversion occurs aloft such as a frontal or subsidence inversion a plume released beneath the inversion will be trapped beneath it. Even if the diffusion is good beneath the inversion such as a coning plume,

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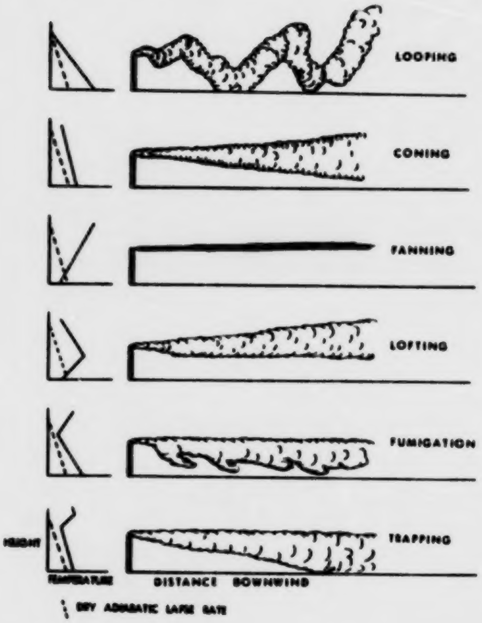
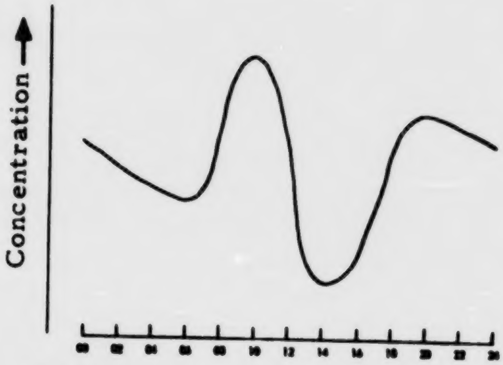
the limit to upward diffusion will increase concentration in the plume and at ground level.

The six plume classes are diagrammed in the accompanying figure.



VARIATION OF POLLUTANT CONCENTRATIONS DUE TO METEOROLOGIC VARIATIONS

An example of the diurnal variation of pollutant concentrations is given in this figure. These are the concentrations some distance down-wind from a continuous elevated urban source on a day when stability reaches extremes, i.e., on a clear day with light winds. This shows only the variations on the order of an hour's duration rather that the rapid variations which may occur a few minutes duration.



Diurnal Variations of Ground-Level Concentrations from Elevated Urban Sources

The primary maximum around 10 AM is due to fumigation. The rapid decrease in concentration following this is due to the heating of a progressively deeper layer and mixing of pollutants through this layer.

The increase of concentrations during the late afternoon are due to the slight increase in stability after the period of maximum heating. During this period the lapse rate is generally changing from strong lapse to weak lapse.

The secondary maximum that occurs in the evening is a phenomena observed only in the urban area. During the late afternoon and early evening a radiation inversion begins to form at the earth's surface in the non-urban areas, i.e., the surrounding countryside. The air over the city, however, does not have a radiation inversion in the lower layers due to release of heat from the buildings and pavings of the city. However, later in the evening, an inversion above the weak lapse layer forms above the city and a mixing of the pollutants in this layer produces the higher concentrations. This has been described by Munn and Katz

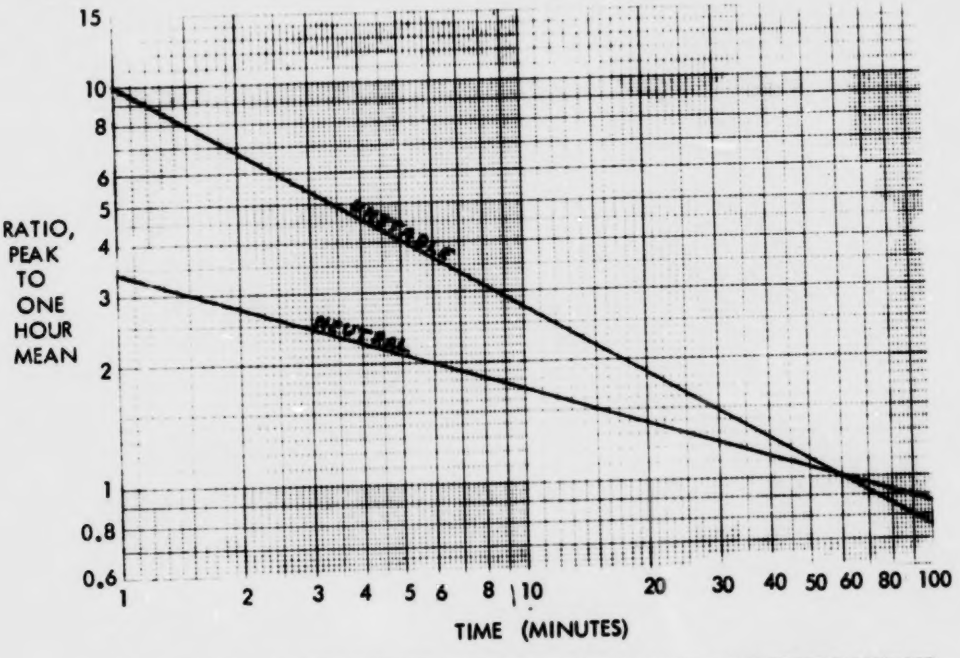
(1959). Hewson (1960) refers to this as a "Type II Fumigation".

When the base of this inversion aloft lowers enough so that the elevated emissions are into the inversion layer the concentrations decrease and continue to decrease until after sunrise. Then surface heating is sufficient to produce mixing beneath the inversion and pollution previously in the inversion layer is mixed through the layer of super-adiabatic lapse rate beneath the remaining upper portion of the inversion resulting in high ground level concentrations.

VARIATION IN CONCENTRATION AS AFFECTED BY SAMPLING TIME

Since the motions of the atmosphere are not constant with time the concentrations of pollutants are also variable with time. Mean concentrations of pollutants measured over different time periods are not directly comparable. This is due principally to the fluctuation of the horizontal wind direction. If sampling is conducted downwind from a source a short sample of 3 to 5 minutes duration will yield a certain concentration but as the sampling interval is increased to say an hour, the mean concentration will decrease due to short periods of time when the wind is not blowing directly from the source to the receptor even though the mean wind throughout the sampling interval is from source to receptor.

Relations have been experimentally determined (Stewart, Gale and Crooks, 1958; Cramer, 1959; and Singer, 1961) relating the peak short term concentration over larger sampling intervals. The accompanyin graph shows some of these findings. This shows that under neutral conditions the peak 3 minute concentration over an hour is about 2 1/2 times the hourly mean. Under unstable conditions when the vertical direction of the wind is also rapidly changing the peak 3 minute concentration can be expected to be about 5 1/2 times the hourly concentration. It should be remembered that this graph is applicable to peak centerline concentration. Off axis concentration would be higher as the averaging time interval is lengthened.



RELATION OF PEAK SHORT TERM CENTERLINE CONCENTRATIONS TO ONE HOUR MEAN CONCENTRATIONS

Where there are multiple sources of the measured pollutant the variation of the wind does not have as large an effect on the changes of concentration with sampling time. A study (McCormick and Xintaras) on carbon monoxide concentrations in Nashville, Tennessee has shown, as an example, 3 minute peak concentration on the order of 1.5 times hourly concentrations.

An empirical mathematical relationship has been proposed for relating peak to one-hour mean concentrations.

$$\frac{X_{\text{peak}}}{X_{1 \text{ hour mean}}} = \left(\frac{3600}{t}\right)^{r}$$

where:

t = time in seconds
r = 0.65 very unstable (class A)
0.52 unstable (class B, C)
0.35 neutral (class D)

Additional studies have analyzed the concentration of specific pollutants by averaging time and frequency of occurrence a selected concentration is exceeded, (Zimmer and Larsen, 1965; Larsen et al, 1967). However, meteorological variations, especially stability conditions, were not explicitly considered.

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INFLUENCE OF TOPOGRAPHY ON TRANSPORT AND DIFFUSION

D. B. Turner*
J. L. Dicke*

In many cases the transport and diffusion of air pollutants is complicated by terrain features. Most large urban areas are located either in river valleys or on the shores of lakes or oceans. Both of these features alter meteorologic conditions.

VALLEY EFFECTS

Channeling

Although the more extreme effects of a valley location occurs when the general flow is light, valleys tend to channel the general flow along the valley axis resulting in a bi-directional wind frequency distribution.

Slope and Valley Winds

When the general wind flow is light and skies are clear, the differences in rates of heating and cooling of various portions of the valley floor and sides cause slight density and pressure differences resulting in small circulations. During the evening hours radiation of heat from the earth's surface and consequent cooling of the ground and air adjacent to the ground causes density changes. The air at point A (Figure 1) is more dense than at point B since point A is nearer the radiating surface. Therefore the more dense air at point A tends to flow in the general direction of B and similarly at other points along the slope. This is the slope wind.

If the slope in Figure 1 is a side of a valley as in Figure 2, the cold air moving down the slopes will tend to drain into the valley floor and deepen with time, intensifying the radiation inversion that would form even without the addition of cold air. Any pollutants that are emitted into this air, because of the inversion structure, will have very limited vertical motion.

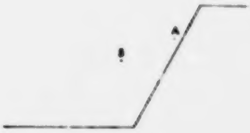

FIGURE 1

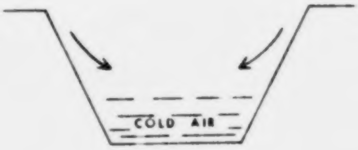

FIGURE 2

If, in addition, the valley floor has some slope, the cold air will have a tendency to move downhill along the valley axis. This is usually referred to as the valley wind (See Figure 3). Because of the necessity of some accumulation of cold air from slope winds, the onset of the valley wind usually lags several hours behind the onset of the slope wind.

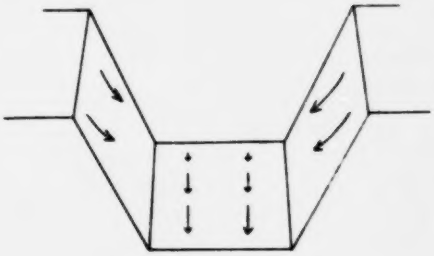

FIGURE 3

The steeper the slopes of the valley, the stronger the slope winds can become. Vegetation will tend to reduce the flow both due to impeding the flow and also restricting the amount of radiation that can take place.

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On a clear day with light winds, the heating of the valley may cause upslope and up-valley winds. However the occurance of upslope and up valley winds is not as frequent nor as strong as the down-slope and down-valley winds, principally due to the fact that down-slope and down-valley winds, due to their density, hug the surfaces over which they travel. Flow in complex valley systems where several valleys merge at angles or slopes vary, usually require special observations to determine flow under various meteorologic conditions.

Inversions Aloft

The trapping of air pollutants beneath inversions aloft is also a problem encountered in valleys. Two types of inversions: warm frontal and subsidence inversions are of particular concern since they are usually slow moving. High concentrations may occur particularly if the layer of air beneath the inversion becomes unstable enough to mix pollutants from elevated sources to ground level (Hewson et al, 1961).

SHORELINE WINDS

The differences in heating and cooling of land and water surfaces and the air above them result in the setting up of circulations if the general flow is light, and in the modification of thermal characteristics and consequently the diffusive abilities of the lower layers of the atmosphere when a general flow occurs.

Sea or Lake Breeze

On summer days with clear skies and light winds the heating of the land surface adjacent to a large lake or the ocean is much more rapid than the heating of the body of water. This results in a temperature difference and consequently a density and pressure difference between the air just above the land surface and the air over the water. Because of the pressure gradient forces, a local circulation is set up with wind from the water toward the land. There is usually some upward motion over the land and subsidence over the water accompanying the sea breeze (Estoque, 1961). There may result a weak transport from land to water aloft completing a cellular structure to the sea breeze. (See Figure 4).

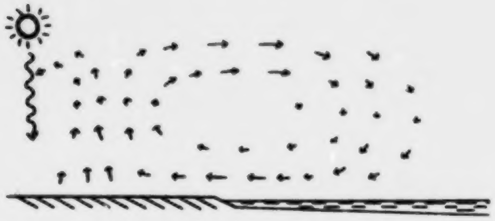


FIGURE 4

In cases where a strong lake breeze occurs, air from quite some distance out over the water may be brought toward the land and due to Coriolus forces acting over the long trajectory the resulting flow will become nearly parallel to the shoreline (Sutton, 1953). This occurs just after the sea breeze is the strongest and results in decreasing the flow normal to the coastline and subsequent breaking down of the sea breeze.

Land Breeze

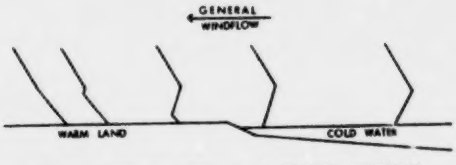
At night the rapid radiational cooling of the land causes lower temperatures above the land surface than over the water. Thus a reverse flow, the land breeze, may result. The land breeze does not usually achieve as high a velocity as the lake breeze, and is usually shallower than the sea or lake breeze.

Of course, any wind flow due to the large scale pressure pattern will alter the local circulation and the flow will be the resultant of the two effects. Usually a light general flow is enough to overshadow the effects of land and sea breezes.

MODIFICATION OF THERMAL STRUCTURE BY BODIES OF WATER

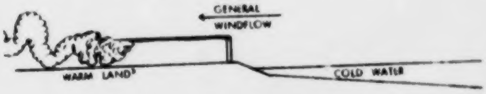
At different seasons of the year and also different times of day the temperature of bodies of water and adjacent land surfaces may be quite different. For example, during the late spring, large bodies of water are still cold relative to adjacent land surfaces and during mid-afternoon this difference is greatest due to the more rapid heating of the land surface. If the general flow in the area is such that the wind has a lengthly trajectory over the water and is blowing toward the shore, an interesting modification of the temperature structure takes place. Because of the passage over the cold water surface, the air will have an inversion in the lower layer as it reaches the shoreline. Any air pollutants released into this inversion will essentially have the characteristics of a fanning plume. As the air passes over the warm land, a strong lapse replaces the inversion near the surface. The depth of this lapse layer becomes deeper as the air moves over more heated land surface. At the point where the lapse layer is deep enough to reach the fanning effluent from an elevated source, fumigation will occur. Fumigation of this type may last considerably longer than the usual diurnal breakup of nocturnal inversions as this fumigation will occur as long as the temperature difference between land and water is maintained and flow from water to land occurs. At greater distances from the shoreline the inversion will be eliminated and looping type of plume behavior will occur. On the other hand, if the source is high enough to be above the lake induced inversion, lofting of the plume would occur until enough distance and consequently enough heating takes place to eliminate the inversion.

Figure 5a indicates the difference in vertical temperature structure that occurs in the above example and Figure 5b indicates the effect this has on the plume characteristics of an elevated shoreline source.



MODIFICATION OF VERTICAL TEMPERATURE STRUCTURE
DUE TO FLOW OVER DIFFERENTLY HEATED SURFACES
(LATE SPRING, AFTERNOON)

FIGURE 5a



EFFECT UPON PLUME CHARACTERISTICS
OF FLOW OVER DIFFERENTLY HEATED SURFACES
(LATE SPRING, AFTERNOON)

FIGURE 5b

At other times when the water is warmer than the land surface (late fall), offshore flow will result in fumigation over the water.

INFLUENCE OF HILLS

The influence of hills upon the transport and diffusion depends upon a number of factors. Whether the source is on the windward or lee side of the hill or ridge is important. A smooth hill will alter the flow least; one with sharp ridges will cause more turbulent eddies to form. The stability of the atmosphere will affect the influence of hills. During stable conditions, the flow will tend to flow around obstructions. Under unstable conditions the tendency is for air to move over obstructions.

When a source is located upwind of a hill or ridge, the pollutants may come in contact with the facing slope, particularly under stable conditions. If the ridge is quite rough, Induced turbulence may cause mixing down to the slope even when the general flow is over the ridge. Wind tunnel studies or field trials with constant level balloons may be desirable to determine the flow under given circumstances.

For a source downwind from a hill or ridge, lee eddies will generally cause considerable downwash of the effluent near the source. If turbulent flow is induced by the hillside, diffusion will be increased but high concentrations very near the stack will result periodically due to the downwash.

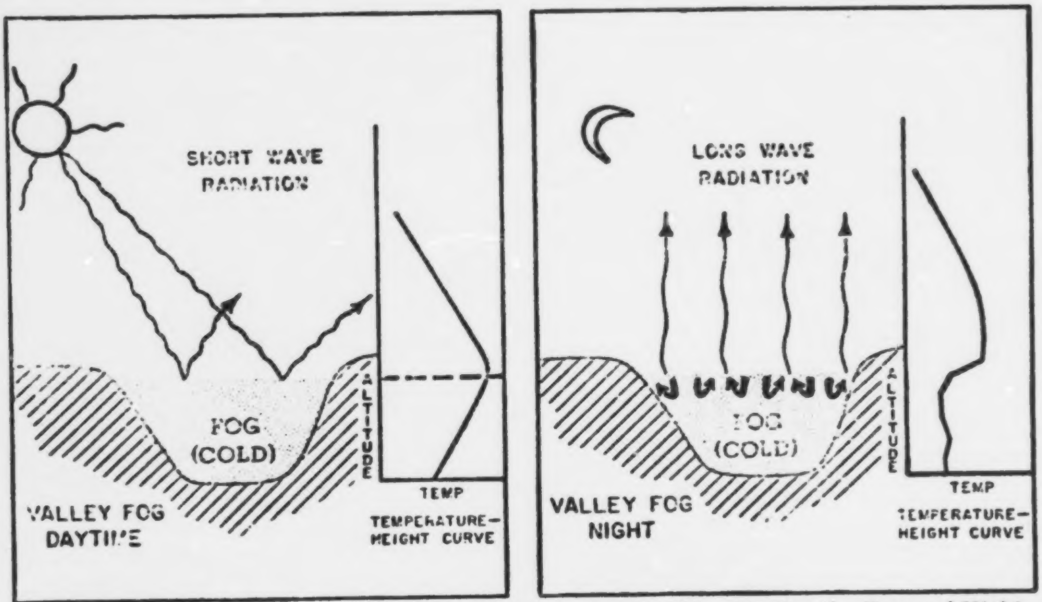
PERSISTENCE OF FOG

The occurrence of fog, together with very stable atmospheric conditions above the earth's surface, has been noted in several air pollution episodes, particularly in Donora, Pennsylvania, in 1948. Under clear skies at night the ground loses much heat because of outgoing radiation and the air in contact with the ground will cool. If, in such cases the air is sufficiently humid, the cooling will bring the air to the saturation point and a fog will form. This is the mechanism which produces radiation fog and is quite common in valley locations. The top of a layer of fog will radiate essentially as a blackbody and cool further, thus forming an inversion layer directly above the fog. As the earth continues to radiate in the infrared, the fog droplets absorb nearly all this heat since the droplet size distribution is similar to the wavelengths of the radiation. Theory and observation have shown that when the top of a fog layer radiates during the night the interior of the layer will become more unstable with time. Increased vertical mixing will occur from below but will be capped by the inversion. Since the air is saturated, an unstable lapse rate will exist if the temperature decrease with height is greater than the moist or pseudo-adiabatic rate of about - 3°F. per 1000 ft., rather than the dry adiabatic lapse rate of - 5.4°F. per 1000 ft.

Thus pollutants that are emitted aloft into an originally stable layer at night and would not normally reach the ground until morning may be contained within a fog layer as the night progresses and be brought to the ground in relatively high concentrations.

After daybreak fogs will often persist for several hours or even the entire day under full sunlight due to the high reflectivity of the top layer. The reflectivity or albedo of thick fogs averages 50% and can be as high as 85%. This delays and lessens the heating of the ground and subsequent evaporation of the fog droplets. An unstable lapse rate may occur above the fog layer but due to lack of surface heating an inversion will often occur within the layer. If high concentrations of particulate pollutants are present, it may be difficult to determine just when the fog has dissipated since particulates scatter and absorb visible light very well and the visibility may remain quite restricted.

Figure 6 illustrates how fog can persist in valley situations and maintain a lid to vertical dispersion.



Persistence of Fog and Corresponding Temperature Profiles During the Day and Night

FIGURE 6

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THE EQUATION OF STATE AND CONVERSION OF CONCENTRATIONS

J. L. Dicke*

The atmosphere may be thought of as a huge thermodynamic engine and meteorologic changes occur through the interaction of temperature, pressure, and density. The relationship between pressure, temperature and volume (thereby density) in gases was determined by early experiments in classical physics. Boyle's law states that when the temperature is held constant the volume of a given mass of perfect gas varies inversely as the absolute pressure. From the law of Gay-Lussac it is known that at constant pressure the volume of a given mass of perfect gas varies directly as the absolute temperature. The equation of state can thus be written in familiar terms:

$$PV = \frac{m}{M} RT$$

where:

P = absolute pressure - dynes/cm^2

V = volume of a gas - cm^3

m = mass of a gas - gm

M = gram-molecular weight/gm-mole

T = absolute temperature - $^{\circ}$K

R = universal gas constant -

$8.31 \times 10^7 \ \frac{\text{dyne cm}}{\text{gm-mole } ^{\circ}\text{K}}$

In most meteorological studies the most useful form of the equation of state or gas law is to express the pressure in millibars and the volume in m^3.

Thus: $1 \text{ mb} = 10^3 \text{ dynes cm}^{-2}$

$1 \text{ m}^3 = 10^6 \text{ cm}^3$

$R = 8.31 \times 10^{-2} \ \frac{\text{mb m}^3}{\text{gm-mole } ^{\circ}\text{K}}$

Example I

A certain power plant emits 0.2 % SO_2 by volume from its stack at a temperature of 260° F. The flow rate of gases emitted is 5×10^5 cu. ft./min. What is the emission rate in units of mass/time (sec.)?

$\frac{m}{t} = \frac{V}{t}\frac{PM}{RT}$ let $P = 980$ mb

$M = 64$

$T = 400^{\circ}$K

$\frac{V}{t} = 2.36 \times 10^2 \text{ m}^3/\text{sec}$

Q = Emission Rate - gm/sec.

$$\frac{m}{t} = \frac{980 \times 2.36 \times 10^2 \times 2 \times 10^{-3} \times 64}{8.31 \times 10^{-2} \times 400} = 890 \text{ gm/sec.}$$

$$Q = \frac{m}{t} = 890 \text{ gm/sec.}$$

Example II

It is known that the air being sampled for SO_2 through a bubbler reaches a temperature of 77°F (T_S) before passing the critical orifice regulating the flow.

What correction must be applied to give the true outside concentration if the temperature is 10°F (T_A), assuming the pressure drop is negligible?

$T_S = 77^{\circ}\text{F} = 298^{\circ}\text{K}$

$T_A = 10^{\circ}\text{F} = 261^{\circ}\text{K}$

The measured concentration will be given by

$$\frac{m}{V_S} = \frac{PM}{RT_S}$$

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and the true concentration will be

$$\frac{m}{V_A} = \frac{PM}{RT_A}$$

Thus:

$$\left(\frac{m}{V}\right)_A \times T_A = \left(\frac{m}{V}\right)_S \times T_S$$

and:

$$\left(\frac{m}{V}\right)_A = \left(\frac{m}{V}\right)_S \times \frac{298}{261} = \left(\frac{m}{V}\right)_S \times 1.14$$

A 14 % correction must be added to the sample concentration to give the concentration outside.

Example III

The measured SO_2 concentration after correction for temperature differences is reported as 44 μgm/m^3. The air temperature is 44°F and the pressure is 987 mb. What is the volume concentration in parts per hundred million under these conditions?

$$T = 44^{o}F = 280^{o}K$$

$$V = \frac{mRT}{MP} = \frac{44 \times 10^{-6} \times 8.31 \times 10^{-2} \times 280}{64 \times 987} = 0.016 \times 10^{-6}\,m^3\ SO_2$$

In one m^3 of air, therefore:

$$\frac{V_{SO_2}}{V_{air}} = \frac{0.016 \times 10^{-6}\,m^3\ SO_2}{1.0\,m^3\ air} = 1.6\ \text{pphm}$$

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METEOROLOGICAL ROSES

D. B. Turner*
L. E. Truppi*

A wind rose is defined in the Glossary of Meteorology as, "Any one of a class of diagrams designed to show the distribution of wind direction experienced at a given location over a considerable period; it thus shows the prevailing wind direction. The most common form consists of a circle from which eight or sixteen lines emanate, one for each compass point. The length of each line is proportional to the frequency of wind from that direction; and the frequency of calm conditions is entered in the center. Many variations exist. Some indicate the range of wind speeds from each direction; some relate wind direction with other weather occurrences." Wind roses may be constructed for data from a given time period such as a particular month or may be for a particular time of day or season from a number of years data. In constructing or interpreting wind roses it is necessary to keep in mind the meteorological convention that wind direction refers to the direction from which the wind is blowing. A line or bar extending to the north on a wind rose indicates the frequency of winds blowing from the north, not the frequency of winds blowing toward the north. Some of the specialized wind roses that may be constructed are precipitation wind roses, stability wind roses, and pollution wind roses. The latter two require additional data than are generally available at standard Weather Bureau stations. An informative article on the history and variants of wind roses has been published by Court.(1)

WIND ROSES - DATA AND PRESENTATION

Prior to January 1964 the surface wind direction was reported by U.S. Weather Bureau stations as one of the 16 directional points corresponding to the mariner's compass card or compass rose, on which each direction is equivalent to a 22 1/2 sector of a 360° circle. Table 1 illustrates a 16-point wind rose summary in the form of a frequency table of wind direction versus wind speed groups. It is an example of wind roses prepared as summaries of hourly observations published monthly until January 1964 in the Local Climatological Data (LCD) Supplement. Frequencies are totaled by direction and wind speed group; a quick look at this wind rose indicates the highest directional frequency is from the ENE and the highest speed frequency is the 8 to 12 mph column. Average speeds have been computed for each direction.

When wind roses are employed to summarize climatological data involving long periods of record, percentage frequencies are favored over numerical totals for tabular presentation since the number of observations in any one cell can become too large. Moreover, wind rose diagrams can be drafted directly from tabular data if percentages are available. Table 2 presents 10 years of hourly wind data observed at New Orleans Moisant International Airport during January for the years 1951 through 1960, as published in the "Decennial Census of United States Climate".(5) This 10-year summary of meteorological data is compiled for most U.S. Weather Bureau first order stations. See Section VII - Sources of Meteorological Data.

On January 1, 1964 the U.S. Weather Bureau changed the wind direction reporting procedure from 16 points to 36 - 10° intervals. Table 3 is the result; a 36-point wind rose. Since 36 cannot be divided by 16, there is no way of grouping 36 points into 16 points and there is no easy way of combining wind data if wind rose summaries are required that include both 16-point and 36-point wind direction observations.

Besides this feature of incompatibility, other problems have developed with the 36-point wind system; first, a 36-point system tends to spread tabulated frequencies and obscure directional significance; second, a list of

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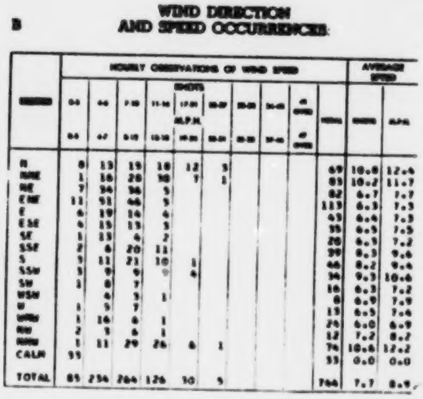
Table 1

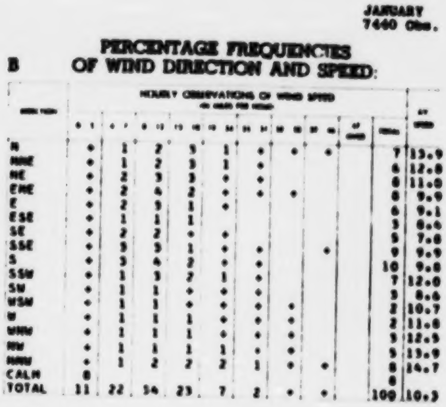


B

WIND DIRECTION
AND SPEED OCCURRENCES:

DIRECTION	HOURLY OBSERVATIONS OF WIND SPEED										AVERAGE SPEED	
	KNOTS 0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	41 & OVER	TOTAL	KNOTS	M.P.H.
	M.P.H. 0-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & OVER			
N	0	13	19	18	12	5				69	10.8	12.4
NNE	1	16	28	30	7	1				83	10.2	11.7
NE	7	34	36	5						82	6.7	7.7
ENE	11	51	46	5						113	6.3	7.3
E	6	19	14	4						43	6.4	7.3
ESE	4	15	13	3						35	6.5	7.5
SE	1	13	4	2						20	6.3	7.2
SSE	2	6	20	11						39	8.3	9.6
S	3	11	21	10	1					46	8.2	9.4
SSW	3	9	9	9	4					36	9.3	10.6
SW	1	8	7							16	6.3	7.2
WSW		4	3	1						8	6.9	7.9
W	1	5	7							13	6.5	7.4
WNW	1	16	8	1						29	6.0	6.9
NW	2	3	6	1						12	7.2	8.2
NNW	1	11	29	26	8	1				76	10.6	12.2
CALM	33									33	0.0	0.0
TOTAL	85	236	264	126	30	5				744	7.7	8.9

Table 1. New Orleans, Louisiana, Moisant International Airport, January, 1963.



JANUARY
7440 Obs.

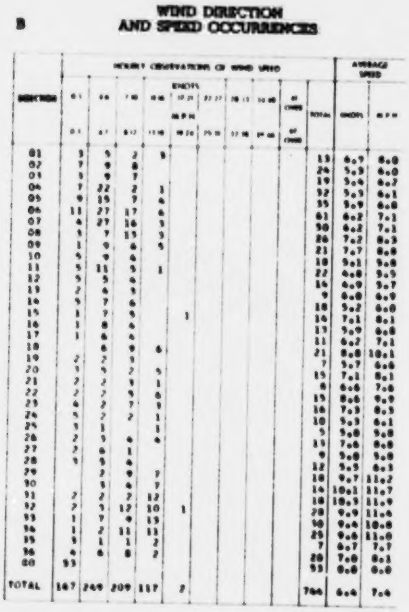
B

PERCENTAGE FREQUENCIES
OF WIND DIRECTION AND SPEED:

DIRECTION	HOURLY OBSERVATIONS OF WIND SPEED (IN MILES PER HOUR)										
	0-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & OVER	TOTAL	AV. SPEED
N	+	1	2	3	1	+	+	+		7	13.9
NNE	+	1	2	3	1	+				6	12.0
NE	+	2	3	3	+	+				8	11.0
ENE	+	2	4	2	+	+	+			8	9.9
E	+	2	3	1	+					6	9.1
ESE	+	1	1	1						3	8.6
SE	+	2	2	+	+					5	7.8
SSE	+	3	3	1	+	+		+		9	9.9
S	+	3	4	2	+	+				10	9.0
SSW	+	1	3	2	1	+				7	12.0
SW	+	1	1	+	+	+				3	8.6
WSW	+	1	1	+	+	+	+			2	10.7
W	+	1	1	1	+	+	+			2	11.8
WNW	+	1	1	1	+	+	+			3	12.5
NW	+	1	1	1	1	+	+			5	13.9
NNW	+	1	2	2	2	1	+	+		8	14.7
CALM	0									0	
TOTAL	11	22	34	23	7	2	+	+		100	10.3

Table 2. New Orleans, Louisiana, Moisant International Airport, 10-Year Summary January 1951-1960. + indicates more than 0 % but less than 0.5 %.

Table 3. 36 point Wind Rose Tabulation New Orleans, Louisiana, Moisant International Airport, Central Standard Time, January 1964.



B

WIND DIRECTION
AND SPEED OCCURRENCES

DIRECTION	HOURLY OBSERVATIONS OF WIND SPEED										AVERAGE SPEED	
	KNOTS 0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	41 & OVER	TOTAL	KNOTS	M.P.H.
	M.P.H. 0-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 & OVER			
01	3	5	2	3						13	6.9	8.0
02	7	9	8							24	5.3	6.0
03	3	9	7							19	5.4	6.2
04	7	22	2	1						32	5.3	6.1
05	9	15	7	4						35	5.9	6.8
06	11	27	17	6						61	6.2	7.1
07	4	27	16	3						50	6.2	7.1
08	3	7	13	3						26	7.2	8.3
09	1	9	6	5						21	7.7	8.8
10	5	9	4							18	5.1	5.8
11	5	11	5	1						22	4.8	5.5
12	5	5	6							16	4.9	5.7
13	2	4	3							9	6.0	6.9
14	5	7	6							18	5.2	6.0
15	1	7	5		1					14	7.1	8.1
16	1	8	4							13	5.9	6.8
17	1	6	4							11	6.2	7.1
18		6	9	6						21	8.8	10.1
19	2	2	3							7	5.7	6.6
20	3	5	2	5						15	7.1	8.1
21	2	2	3	1						8	6.6	7.6
22	2	2	5	6						15	8.6	9.9
23	4	2	7	3						16	7.3	8.3
24	5	2	2	1						10	5.3	6.1
25	3	1		1						5	5.0	5.8
26	2	3	4	4						13	7.6	8.8
27	2	6	1							9	5.0	5.8
28	3	5	4							12	5.5	6.3
29		2	9	7						18	9.7	11.2
30		3	6	7						16	10.1	11.7
31	2	2	2	12						18	10.3	11.9
32	2	3	12	10	1					28	9.9	11.4
33	1	7	9	13						30	9.4	10.8
34	1	2	11	11						25	9.6	11.0
35	3	1	1	2						7	6.7	7.7
36	4	6	8	2						20	7.0	8.1
00	33									33	0.0	0.0
TOTAL	147	249	209	117	2					744	6.4	7.4

36 directions is often too lengthy for convenience; lastly, it is almost impossible to construct the standard radial bar-type wind rose with 36 bars. The bars crowd together at the center, and variations of radial length, proportional to directional percentage frequency between given wind directions are minimized.

The 36-point wind reporting procedure has been in effect since 1964 and it has been found that the disadvantages may be offset by using a 12-point or 30° sector wind rose. Table 4 was constructed from Table 3 by grouping frequencies into 30° intervals. Directional discrimination is not as fine as in a 16- or 36-point breakdown, but the tabulation is concise and a bar diagram can be easily constructed.

POLLUTION WIND ROSES

The increasing emphasis on identifying and abating air pollution problems has resulted in the establishment of air sampling networks which determine concentrations of pollutants on a time scale as short as 5 minutes. Since transport of pollutants depends in great part on wind flow, an appropriate wind rose diagram would be very helpful in relating air pollutant and wind data. Figures 1 and 2 illustrate a type of pollution wind rose devised for the air pollution abatement study conducted in the Parkersburg, West Virginia - Marietta, Ohio region.[(3)]

Figure 3 shows three wind recording and SO_2 gas sampling sites that were installed at Parkesburg, Vienna, West Virginia and Marietta, Ohio from October 1965 through February 1966. The bar-type wind roses for

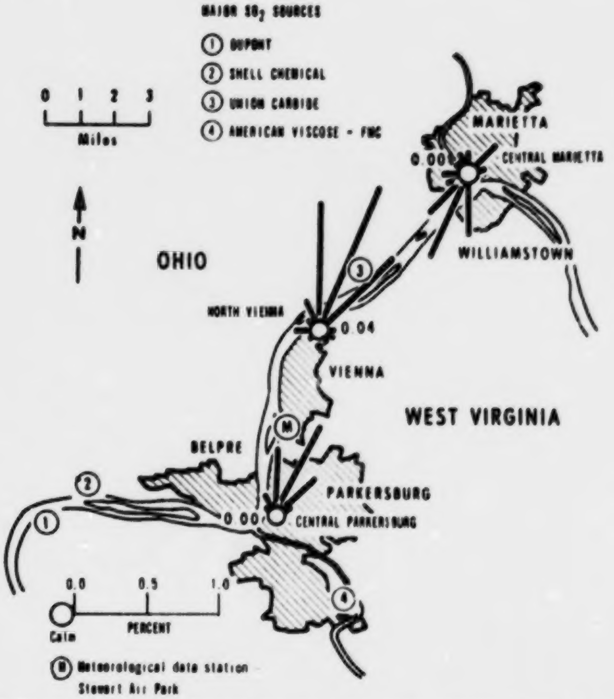
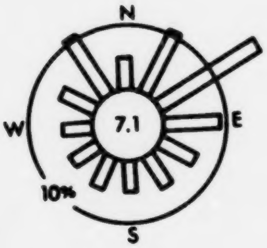

MAJOR SO₂ SOURCES
① DUPONT
② SHELL CHEMICAL
③ UNION CARBIDE
④ AMERICAN VISCOSE - FMC
0 1 2 3
Miles
N
OHIO
MARIETTA
0.00
CENTRAL MARIETTA
WILLIAMSTOWN
NORTH VIENNA
0.04
VIENNA
WEST VIRGINIA
BELPRE
PARKERSBURG
0.00
CENTRAL PARKERSBURG
0.0 0.5 1.0
Calm
PERCENT
Ⓜ Meteorological data station - Stewart Air Park

Figure 1. SO_2 Pollution Roses for Concentrations >0.10 ppm, October 1965 through February 1966.

Table 4

New Orleans, Louisiana
Moisant International Airport
January 1964
12-Point Wind Rose

DIRECTION	0-3	4-7	8-12	13-18	18-24	25-31	32-38	74-40	Tot.	AVSPD (mph)
N 35-36-01	10	12	11	7					40	7.9
NNE 02-03-04	17	40	17	1					75	6.1
ENE 05-06-07	24	69	40	13					146	7.0
E 08-09-10	9	25	23	8					65	7.6
ESE 11-12-13	12	20	12	1					45	6.0
SSE 14-15-16	7	22	15		1				45	7.0
S 17-18-19	3	14	16	6					39	7.9
SSW 20-21-22	7	9	10	12					38	8.5
WSW 23-24-25	12	5	9	5					31	6.7
W 26-27-28	7	14	9	4					34	7.0
WNW 29-30-31	2	7	15	26					50	11.6
NWW 32-33-34	4	12	32	34	1				83	11.1
CALM	53								53	
Tot.	167	249	208	117	2				744	7.4



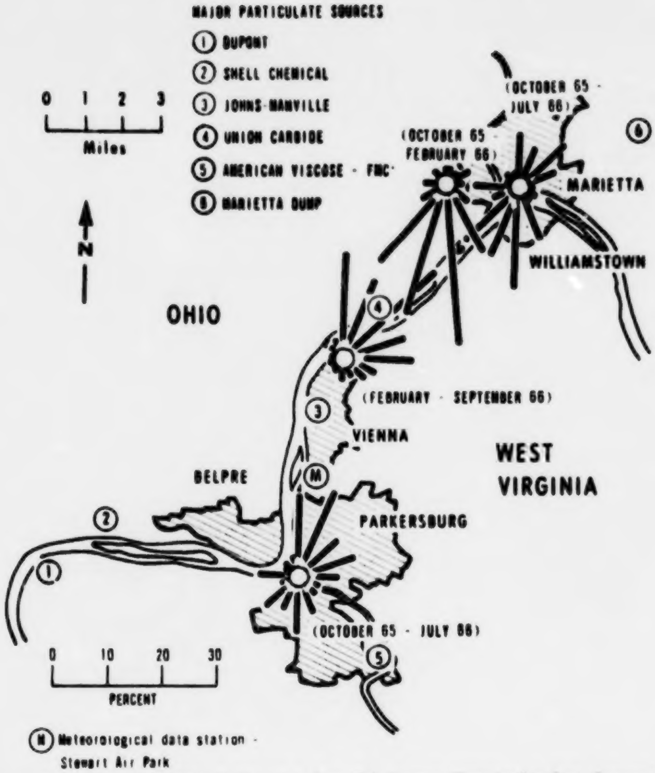
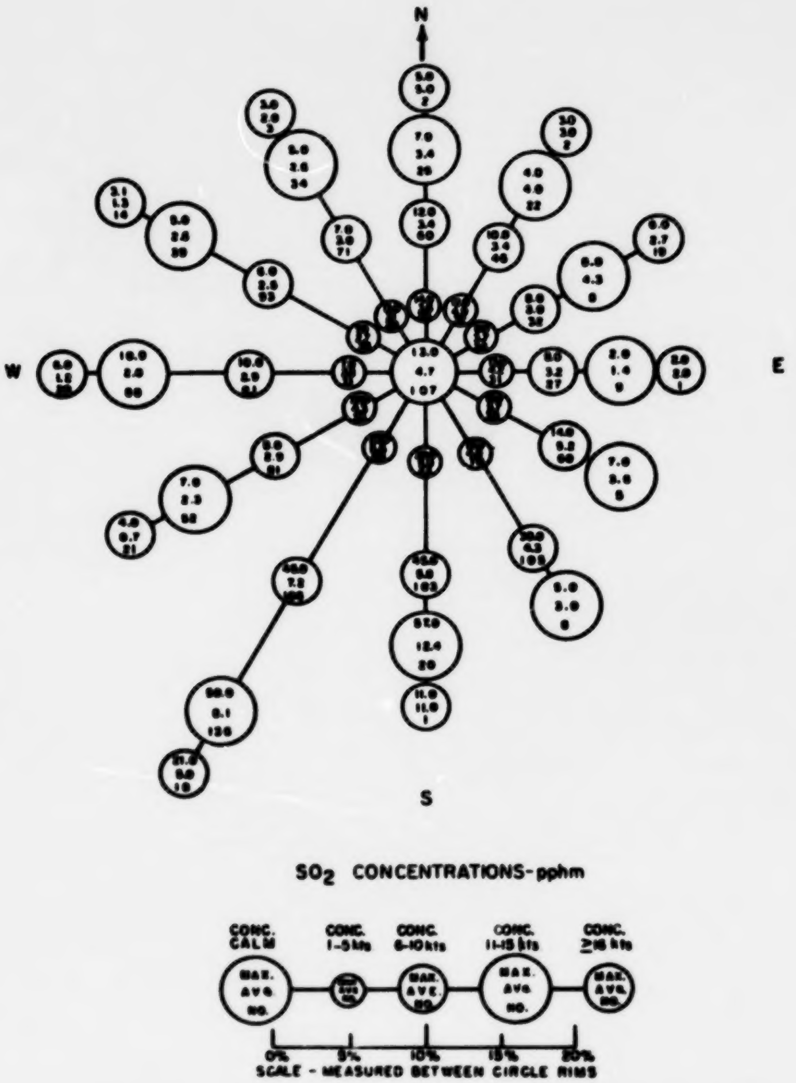

MAJOR PARTICULATE SOURCES
① DUPONT
② SHELL CHEMICAL
③ JOHNS-MANVILLE
④ UNION CARBIDE
⑤ AMERICAN VISCOSE - FMC
⑥ MARIETTA DUMP
0 1 2 3
Miles
N
OHIO
WEST VIRGINIA
(OCTOBER 65 - JULY 66)
(OCTOBER 65 - FEBRUARY 66)
MARIETTA
WILLIAMSTOWN
(FEBRUARY - SEPTEMBER 66)
VIENNA
BELPRE
Ⓜ
PARKERSBURG
(OCTOBER 65 - JULY 66)
0 10 20 30
PERCENT
Ⓜ Meteorological data station - Stewart Air Park

Figure 2. Hourly Wind Roses for 24-hour Periods for Suspended Particulate Concentrations >200 μg/m^3 and average Wind Speed >3 mph.

each site location represent only winds coincident with SO_2 concentrations greater than 0.10 ppm. Winds observed when the SO_2 concentration was equal to or less than 0.10 ppm were ignored in computing percentage frequencies. Figure 1 graphically identifies the major source of high SO_2 emissions as source 3; the Union Carbide Company plant.

Figure 2 is similiar to Figure 3 except the pollutant sampled was suspended particulate matter on a 24-hour basis. Another Hi-vol Sampler was in operation west of Marietta, Ohio. Since pollutant sampling was on a 24-hour basis, 24-hourly winds were tabulated, but only for periods when particulate concentrations were greater than 200 μg/m^3 and when the average wind speed over the 24 hours was greater than 3 mph. Again the pollutant rose points to the Union Carbide Company plant, source 4, as the major contributor.

Special wind instruments were installed for this abatement study, and the investigators chose to reduce the autographic wind data on direction to a 16-point tabulation. Because of this decision, 36-point wind data recorded at site M, Stewart Air Park, were used only to determine average wind conditions. It was also decided to omit the usual wind speed grouping in the pollution wind roses.



COINCIDENT WIND ROSE—CINCINNATI, OHIO, DEC-JAN-FEB, 1964

Figure 3

A more detailed pollution wind rose is displayed in Figure 3. Coincident wind data and SO_2 concentrations (pphm) for the winter months of 1964 are summarized: hourly wind data were recorded by the U.S. Weather Bureau at Greater Cincinnati Airport and pollutant data by the U.S. Public Health Service at a downtown Cincinnati location.(4) Speed groups are denoted by different sized circles, instead of the usual bar-thickness, and percentage frequency of each speed group is indicated by radial distance between circle rims. Inside each circle are listed pollutant statistics coincident with the particular direction and speed group. These are: maximum SO_2 concentration recorded, the average concentration, and the number of concentration values observed. The value of this type of pollution wind rose is demonstrated in Figure 3 where the highest maximum and average SO_2 concentrations are readily identified with S or SSW winds of 11 to 15 knots.

REMOVING BIAS IN 16-POINT WIND ROSES

Wind direction, such as for hourly airport observations where no recorder is used, is determined by an observer watching the wind direction indicator dial for one minute and recording direction to 16 points. It has been found that one of the eight principal directions (N, NE, E, etc.) is more frequently recorded than are the secondary directions (NNE, ENE, ESE, etc.). Depending upon the purpose of constructing a wind rose, it may be desirable to remove this bias. Removal of the bias may be by total frequencies of each direction or by wind speed classes. In order to determine if there is bias, the sums should be determined separately for the principal direction frequencies (N_e) and the secondary direction frequencies (N_o). Bias usually occurs if one exceeds the other on the order of 10 to 20%. **Assuming that the sum of the principal frequencies (N_e) exceeds the sum of the secondary frequencies (N_o) the frequencies have the bias removed by subtracting**

$$n_e\left(\frac{N_e - N_o}{2\ N_e}\right)$$

from the frequency of each primary direction where n_e is the frequency for that direction and adding

$$n_o\left(\frac{N_e - N_o}{2\ N_o}\right)$$

to the frequency of each secondary direction where n_o is the frequency for the secondary direction.

DISTRIBUTION OF CALMS

In some cases, it is also desirable to distribute the calms in the lowest wind speed class among the 16 directions. It is usually better to use the frequencies of the lowest two speed classes (0-7 mph) to distribute the calms in order to have a more respresentative sample of light winds. If N_c is the total number of calms, N_w is the total frequency of winds in the 0-7 mph range, and n_w is the frequency of winds in the 0-7 mph range for one direction, the number of calms assigned to this direction is:

$$\frac{n_w\ N_c}{N_w}$$

Example: Removing Bias in a Wind Rose.

Below is given the wind direction and speed frequencies for October, 1962, for St. Louis Mo.

Table 5. WIND DIRECTION AND SPEED OCCURRENCES

Direction	Hourly observations of wind speed (mph) 0-3	4-7	8-12	13-18	19-24	Total
N	1	5	11	3		20
NNE	5	10	4	1		20
NE	7	9	3	1		20
ENE	5	6	8	3		22
E	2	4	5	1		12
ESE	3	4	3	1		11
SE	13	8	17	6		44
SSE	5	19	21	5		50
S	15	23	26	6		70
SSW	6	29	19	2		56
SW	5	44	33	8		90
WSW	4	17	17	8		46
W	8	25	13	8		54
WNW	4	15	15	14		48
NW	4	3	17	30	6	60
NNW	0	6	18	8		32
CALM	89					89
Total	176	227	230	105	6	744

Problem: To remove the bias by two separate speed classes: 0-7 mph, and $\geq$ 8 mph.

First remove the bias in the 0-7 mph class. Determine N_e and N_o by adding the primary and secondary direction frequencies separately.

Table 6. 0-7 mph FREQUENCIES

N	6	NNE	15
NE	16	ENE	11
E	6	ESE	7
SE	21	SSE	24
S	38	SSW	35
SW	49	WSW	21
W	33	WNW	19
NW	7	NNW	6
N_e =	176	N_o =	138

$$\frac{N_e - N_o}{2N_e} = \frac{176 - 138}{2(176)} = 0.108$$

$$\frac{N_e - N_o}{2N_o} = \frac{176 - 138}{2(138)} = \frac{38}{276} = 0.138$$

Table 7. REMOVING BIAS FOR 0-7 mph CLASS

$n_e - n_e(0.108)$		$n_o + n_o(0.138)$	
N	6 - 1 = 5	NNE	15 + 2 = 17
NE	16 - 2 = 14	ENE	11 + 2 = 13
E	6 - 1 = 5	ESE	7 + 1 = 8
SE	21 - 2 = 19	SSE	24 + 3 = 27
S	38 - 4 = 34	SSW	35 + 5 = 40
SW	49 - 5 = 44	WSW	21 + 3 = 24
W	33 - 4 = 29	WNW	19 + 3 = 22
NW	7 - 1 = 6	NNW	6 + 1 = 7
	156		158

Next, remove the bias for the $\geq$ 8 mph class.

Table 8. $\geq$ 8 mph FREQUENCIES

N	14	NNE	5
NE	4	ENE	11
E	6	ESE	4
SE	23	SSE	26
S	32	SSW	21
SW	41	WSW	25
W	21	WNW	29
NW	53	NNW	26
N_e =	194	N_o =	147

$$\frac{N_e - N_o}{2N_e} = \frac{194 - 147}{2(194)} = 0.121$$

$$\frac{N_e - N_o}{2N_o} = \frac{194 - 147}{2(147)} = 0.160$$

Table 9. REMOVING BIAS FOR $\geq$ 8 mph CLASS

$n_e - n_e(0.121)$		$n_o + n_o(0.160)$	
N	14 - 2 = 12	NNE	5 + 1 = 6
NE	4 - 0 = 4	ENE	11 + 2 = 13
E	6 - 1 = 5	ESE	4 + 1 = 5
SE	23 - 3 = 20	SSE	26 + 4 = 30
S	32 - 4 = 28	SSW	21 + 3 = 24
SW	41 - 5 = 36	WSW	25 + 4 = 29
W	21 - 3 = 18	WNW	29 + 5 = 34
NW	53 - 6 = 47	NNW	26 + 4 = 30
	170		171

The debiased wind frequencies are now completed for the two wind speed classes. It will depend upon the purpose of the wind rose as to whether it is necessary to distribute the 0-7 frequencies between the 0-3 mph and 4-7 mph classes.

Problem: Distribute the calms (decalm) for the above wind frequencies.

$$\frac{N_c}{N_w} = \frac{89}{314} = 0.283$$

Table 10. DISTRIBUTION OF CALMS

Direction	n_w (debiased)		(0.283)
N	5	=	1
NNE	17	=	5
NE	14	=	4
ENE	13	=	4
E	5	=	1
ESE	8	=	2
SE	19	=	5
SSE	27	=	8
S	34	=	10
SSW	40	=	11
SW	44	=	13
WSW	24	=	7
W	29	=	8
WNW	22	=	6
NW	6	=	2
NNW	7	=	2
			89

The resulting debiased and decalmed wind frequencies in the usual classes are as follows with distributed calms shown in parenthesis.

Table 11. WIND DIRECTION AND SPEED OCCURRENCES, ST. LOUIS, MO. OCTOBER, 1962

BIAS REMOVED AND CALMS DISTRIBUTED
(Distributed Calms in Parenthesis)

	Wind speed class (mph)					
Direction	0-3	4-7	8-12	13-18	19-24	Total
N	1 (1)	4	9	3		18
NNE	6 (5)	11	5	1		28
NE	6 (4)	8	3	1		22
ENE	6 (4)	7	9	4		30
E	2 (1)	3	4	1		11
ESE	3 (2)	5	4	1		15
SE	12 (5)	7	15	5		44
SSE	6 (8)	21	24	6		65
S	13 (10)	21	23	5		72
SSW	7 (11)	33	22	2		75
SW	4 (13)	40	29	7		93
WSW	5 (7)	19	20	9		60
W	7 (8)	22	11	7		55
WNW	5 (6)	17	18	16		62
NW	3 (2)	3	15	27	5	55
NNW	1 (2)	6	20	9	1	39
Total	176	227	231	104	6	744

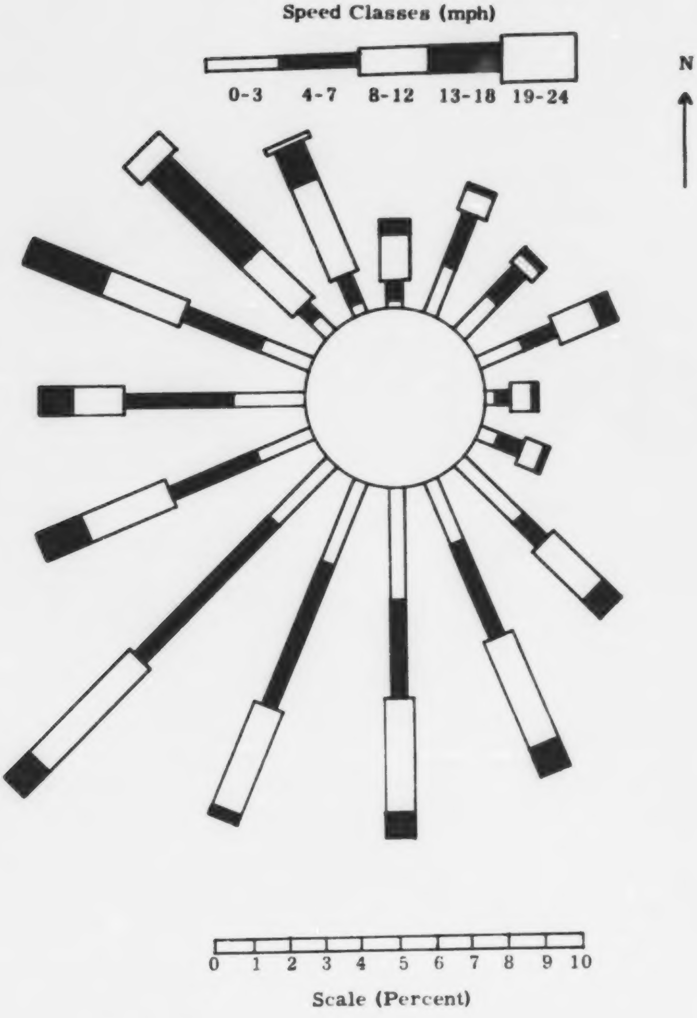
Figure 4 is a wind rose drawn from these frequencies.

Figure 4

Wind Rose

St. Louis October 1962

Bias Removed and Calms Distributed



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SECTION THREE

ATMOSPHERIC DIFFUSION

Principles of Turbulence and Diffusion
Introduction to Turbulence and Diffusion Theory
The Generalized Gaussian Diffusion Equation
Atmospheric Diffusion Computations
Effective Stack Height

PRINCIPLES OF TURBULENCE AND DIFFUSION

D. H. Pack* and J. L. Dicke**

When a small concentrated puff of gaseous pollutant is released into the atmosphere, it tends to expand in size due to the dynamic action of the atmosphere. In doing so, the concentration of the gaseous pollutant is decreased because the same amount of pollutant is now contained within a larger volume. This natural process of high concentration spreading out to lower concentrations is the process of diffusion.

Atmospheric diffusion is ultimately accomplished by the wind movement of pollutants, but the character of the source of pollution requires that this action of the wind be taken into account in different ways.

These sources can be conveniently grouped into three classes: point sources, line sources, and area sources. In practice, the first two classes must be further divided into instantaneous and continuous sources.

The instantaneous point source is essentially a "puff" of material created or ejected in a relatively short time, as by a nuclear explosion, the sudden rupture of a chlorine tank, or the bursting of a tear-gas shell. The wind of immediate importance is, of course, that occurring at the place and time at which the pollutant is created. Since the wind is highly variable, the initial direction of movement of the puff is also variable and difficult of prediction; a soap-bubble pipe and five minutes' close observation of the initial travel of successive bubbles will convincingly demonstrate the difficulty of predicting the exact trajectory of the next bubble. In addition, dilution of a puff source is a very strong function of time after its release. At first, the small-scale fluctuations of the wind cause it to grow rather slowly and the larger-scale wind variations simply carry it along on erratic paths. But as the puff grows, larger-scale motions can get a "hold" on it to tear it apart and dilute it more rapidly. Thus, the unique feature of the instantaneous point source is its increasing dispersion rate with time, whence the necessity to consider successively larger scales of meteorological phenomena in calculating its spread.

Continuous point sources (the smoke plume from a factory chimney, the pall from a burning dump) are the most familiar, the most conspicuous, and the most studied of pollution sources. The meteorology of the continuous source must take into account the time changes of the wind at the point of emission. The behavior of a plume from a factory chimney is very much like that of water from a hose being played back and forth across a lawn. It is evident that if the hose is steady the same area will be continually exposed to the water. But if the hose (wind) moves back and forth in an arc, the water (pollution) will be distributed over a wider area, hence the concentration will be less. For a truly continuous source there are other changes of great importance - primarily the diurnal and seasonal cycles.

The isolated line source is less common and therefore of less general interest, with two important exceptions - heavily traveled highways, and the swath of chemicals emitted by cropdusting apparatus. In both these examples, if the line of pollutant is uniform and is long enough, the dispersion of the pollution must be attained in only two dimensions, along the wind and in the vertical. If the line source is a continuous one, as might be the case of a freeway in rush hours, spreading in the downwind direction becomes ineffective (at a particular downwind location), so that only the vertical dimension is left to provide dilution. This behavior of the continuous line source has been exploited by meteorologists in field experiments with controlled tracers to permit the detailed study of vertical diffusion, uncomplicated by effects in the other two coordinates.

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The area source can vary enormously in size. It may be distributed over several square kilometers, as in an industrial park, over tens or hundreds of square kilometers, as in a city, or over thousands of square kilometers, exemplified by the almost continuous strip city (the "megalopolis" or "megapolitan area") along the eastern seaboard of the United States. These area sources usually include combinations of all the single-source configurations. A large city will include many thousands of home chimneys, thousands of factories and shops, hundreds of kilometers of streets, open dumps, burning leaves, evaporating fumes from gasoline storage or from cleaning plants and paint factories, and everywhere the automobile. The weather problem of the city area source becomes, in the aggregate, quite different from that of a single source. Here we are concerned not with the increasing rate of wind dispersion with increasing scale, or with the behavior of wind with time at a single point, but rather with the replenishment rate of the air over the city. We must consider the total movement of a large volume of air as it "ventilates" the city. Anything that reduces this ventilation rate, whether it be the confining effect of surrounding mountains or the reduced velocities of a slow-moving anticyclone, is of concern.

In the construction of cities man has modified the weather. The volume of effluent injected into the air has reduced the solar radiation. The absorption characteristics of cement and asphalt instead of grass and trees create urban "heat islands." These effects must be considered in the meteorology of urban air pollution.

The atmosphere disperses pollutants because it is in constant motion, and this motion is always turbulent to some degree. There is as yet no fully accepted definition of turbulence, but empirically it can be described as random (three-dimensional) flow. There is as yet no complete explanation for the complexities even of controlled wind-tunnel turbulence, hence it is not surprising that the understanding of turbulent diffusion in the atmosphere has progressed largely through empirical treatments of controlled tracer experiments. The current tendency is to deal with turbulence through statistical concepts derived from aerodynamics and fluid dynamics. This treatment, with its emphasis on the detailed properties of the turbulence, is in contrast to earlier theories which centered around a virtual-diffusivity concept based on analogy with molecular diffusion. In the practical application of computing pollution concentrations, it is more usual to employ the statistical method for distances to perhaps 150 kilometers from the source, and equations based on virtual-diffusivity ("K") theory for longer distances, particularly for calculations on a hemispheric or global scale.

Vertical Turbulent Diffusion

To all intents and purposes rapid atmospheric diffusion in the vertical is always bounded: on the bottom by the surface of the earth and at the top by the tropopause. The tropopause - the demarcation between the troposphere, where temperature decreases with altitude, and the stratosphere, where the temperature is relatively constant or increases with altitude - is lowest over the poles, at about 8 kilometers, and highest in the tropics, about 20 kilometers. The detection of radon products throughout the troposphere is conclusive evidence of the eventual availability of the full depth of the troposphere for vertical dispersion, since the radon source is exclusively at the earth's surface. Utilization of this total vertical dimension can take place at very different rates, depending on the thermally driven vertical wind. These rates are intimately related to the vertical temperature profile. On the average (and if we neglect the effects of the phase change of water in the air), enhanced turbulence is associated with a drop in temperature with height of 10°C per kilometer or greater. (This is the dry adiabatic rate.) If the temperature change with height is at a lesser rate, turbulence tends to be decreased, and if the temperature increases with height (an "inversion"), turbulence is very much reduced.

The temperature profiles particularly over land, show a large diurnal variation as seen in Figure 1. Shortly after sunrise the heating of the land surface by the sun results in rapid warming of the air near the surface; the reduced density of this air causes it to rise rapidly. Cooler air from aloft replaces the rising air "bubble," to be warmed and rise in turn. This vigorous vertical interchange creates a "superadiabatic" lapse rate - a temperature decrease of more than 10°C per vertical kilometer - and vertical displacements are accelerated. The depth of this well-mixed layer depends on the intensity of solar radiation and the radiation characteristics of the underlying surface. Over the deserts this vigorous mixing may extend well above 3 kilometers, while over forested lake country the layer may be only one or two hundred meters thick. Obviously, this effect is highly dependent on season, in winter the lesser insolation and unfavorable radiation characteristics of snow cover greatly inhibit vertical turbulence.

In contrast, with clear or partly cloudy skies the temperature profile at night is drastically changed by the rapid radiational cooling of the ground and the subsequent cooling of the layers of air near the surface. This creates an "inversion" of the daytime temperature profile, since there is now an increase in temperature with height. In such a situation the density differences rapidly damp out vertical motions, tend to reduce vertical turbulence, and stabilize the atmosphere.

Two other temperature configurations, on very different scales, have important effects on vertical turbulence and the dilution of air pollution. At the smaller end of the scale, the heat capacity of urban areas and, to a lesser extent, the heat generated by fuel consumption act to modify the temperature profile. The effect is most marked at night, when the heat stored by day in the buildings and streets warms the air and prevents the formation of the surface-based temperature inversion typical of rural areas. Over cities it is rare to find inversions in the lowest 100 meters, and the city influence is still evident 200 to 300 meters above the surface. The effect is a function of city size and building density, but not enough observations are yet available to provide any precise quantitative relations. Although the effect even for the largest cities is probably insignificant above a kilometer, this locally produced vertical mixing is quite important. Pollution, instead of being confined to a narrow layer near the height of emission, perhaps only 100 meters in thickness, can be freely diluted in more than double the volume of air, the concentrations being reduced by a similar factor.

On a much larger scale the temperature profile can be changed over thousands of square kilometers by the action of large-scale weather systems. In traveling storm systems (cyclones) the increased pressure gradients and resulting high winds, together with the inflow of air into the storm, create relatively good vertical mixing conditions. On the other hand, the flat pressure patterns, slower movement, and slow outflow of surface air in high-pressure cells (anticyclones) result in much less favorable vertical mixing. This is primarily due to the gradual subsidence of the air aloft as it descends to replace (mass-continuity requirement) the outflow at the surface. During this descent the air warms adiabatically, and eventually there is created a temperature inversion aloft inhibiting the upward mixing of pollution above the inversion level. As the anticyclone matures and persists, this subsidence inversion may lower to very near the ground and persist for the duration of the particular weather pattern.

Horizontal Turbulent Diffusion

The most important difference between the vertical and horizontal dimensions of diffusion is that of scale. In the vertical, rapid diffusion is limited to about 10 kilometers. But in the horizontal, the entire surface of the globe is eventually available. Even when the total depth of the troposphere is considered, the horizontal scale is larger by at least three orders of magnitude, and

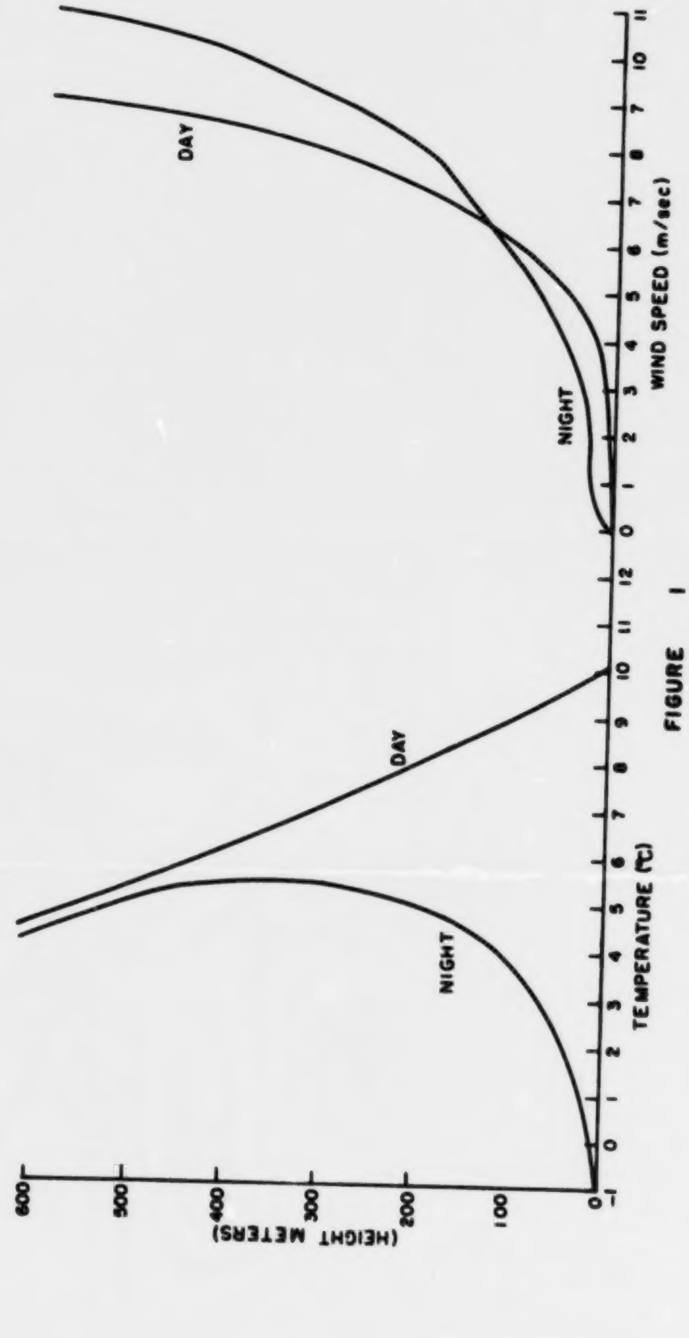

FIGURE 1

Diurnal Variation of Temperature and Wind Speed the difference, say during a nocturnal inversion which might restrict the vertical diffusion to a few tens of meters, is even greater since the lateral turbulence is reduced less than the vertical component. Mechanically produced horizontal turbulence is, on a percentage basis, much less important than the thermal effects; its effects are of about the same order of magnitude as the vertical mechanical effects.

The thermally produced horizontal turbulence is not so neatly related to horizontal temperature gradients as vertical turbulence is to the vertical temperature profile. The horizontal temperature differences create horizontal pressure fields, which in turn drive the horizontal winds. These are acted upon by the earth's rotation (the Coriolis effect) and by surface friction, so that there is no such thing as a truly steady-state wind near the surface of the earth. Wind speeds may vary from nearly zero near the surface at night in an anticyclone to 100 meters per second under the driving force of the intense pressure gradient of a hurricane. The importance of this variation, even though in air pollution we are concerned with much more modest ranges, is that for continuous sources the concentration is inversely proportional to the wind speed.

The variation of turbulence in the lateral direction is perhaps the most important factor of all and certainly one of the most interesting. In practice this can best be represented by the changes in horizontal wind direction illustrated in Figure 2. Within a few minutes, the wind may fluctuate rapidly through 90 degrees or more. Over a few hours it may shift, still with much short-period variability, through 180 degrees, and in the course of a month it will have changed through 360 degrees numerous times. Over the seasons, preferred directional patterns will be established depending upon latitude and large-scale pressure patterns. These patterns may be very stable over many years, and thus establish the wind climatology of a particular location.

The emitted pollution travels with this ever-varying wind. The high-frequency fluctuations spread out the pollutant, and the relatively steady "average" direction carries it off - for example, toward a suburb or a business district. A gradual turning of direction transports material toward new targets and gives a respite to the previous ones. Every few days the cycle is repeated, and over the years the prevailing winds can create semipermanent patterns of pollution downwind from factories or cities.

Description of Gustiness Classifications

The original separation of wind gustiness into typical categories led to the establishment of four classes - A, B, C, and D - in order of decreasing amplitude of the azimuthal fluctuation of the wind. Further analysis indicated the need for a fifth category, and the B class was subdivided into B_1 and B_2. The classifications as developed at Brookhaven and as applied to wind data in this analysis are defined below. The types are further explained by samples of the 500-ft wind records shown in Figure 2.

Type A:	Fluctuations of the wind direction exceeding 90 degrees.
Type B_2:	Fluctuations ranging from 45 to 90 degrees.
Type B_1:	Similar to A and B_2, with fluctuations confined to 15 and 45 degree limits.
Type C:	Distinguished by the unbroken solid core of the trace, through which a straight line can be drawn for the entire hour, without touching "open space." The fluctuations must reach 15 degrees, but no upper limit is imposed.
Type D:	The trace approximates a line. Short-term fluctuations do not exceed 15 degrees.

Types A and B_2 are mainly convective in nature and are associated with great instability. A combination of convective and mechanical turbulence is represented in the B_1 gustiness type, which occurs under conditions of moderate instability. Gustiness class C is primarily mechanical in origin and is associated with neutral stability. Type D, which is found with stable lapse rates, reflects little or no turbulence.

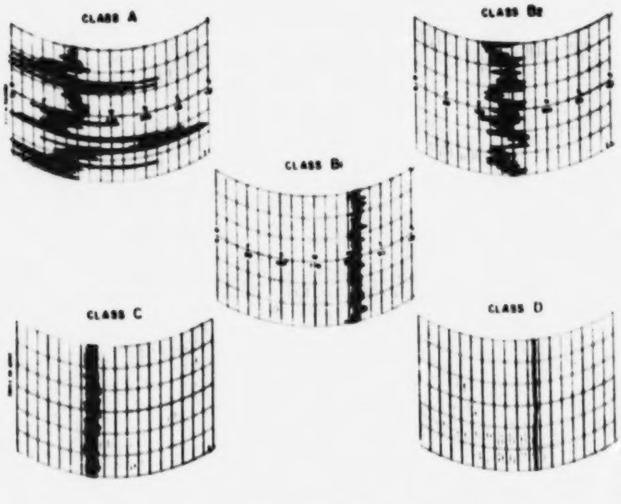

Figure 2. GUISTINESS CLASSIFICATION

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INTRODUCTION TO TURBULENCE AND DIFFUSION THEORY

D. B. Turner*

I TURBULENCE

Turbulence is defined in the Glossary of Meteorology as, "a state of fluid flow in which the instantaneous velocities exhibit irregular and apparently random fluctuations so that in practice only statistical properties can be recognized and subjected to analysis." Assuming that a mean velocity may be defined for a given time period, the turbulent velocity may be considered to be a random fluctuating motion superimposed upon the mean motion. Considering a three dimensional coordinate system with the x and y axis in the horizontal and z in the vertical the components of the instantaneous velocity are:

$u = \bar{u} + u'$ in the x direction

$v = \bar{v} + v'$ in the y direction and

$w = \bar{w} + w'$ in the z direction

where $\bar{u}$, $\bar{v}$, and $\bar{w}$ are the mean velocities and u', v' and w' are the deviations from the mean, the turbulent components or eddy velocities. Usually, the mean flow is horizontal ($\bar{w} = 0$) and the x axis is taken to be in the direction of the mean flow ($\bar{v} = 0$). In this case, the instantaneous velocity is $\bar{u} + u' + v' + w'$. This is shown except for w' in Figure 1.

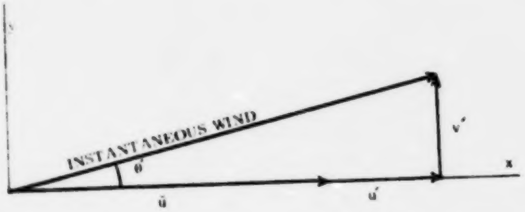

Figure 1. Instantaneous Wind Velocity Components (In Two Dimensions)

The ratio of the eddy velocities to the mean velocity, $u'/\bar{u}$, $v'/\bar{u}$, and $w'/\bar{u}$, are the components of gustiness. The squares of the eddy velocities u'^2, v'^2 and w'^2 are the eddy energies. The mean of these eddy energies indicate the kinetic energy of the motion.

Since the same mean eddy energy, $\overline{u'^2}$, may result from many different combinations of eddy velocities, the mean eddy energy does not specify the turbulence. The ratio of the square root of the mean eddy energy to the mean wind speed $\sqrt{\overline{u'^2}}/\bar{u}$ is referred to as the intensity of turbulence of the u component; $\sqrt{\overline{v'^2}}/\bar{u}$ and $\sqrt{\overline{w'^2}}/\bar{u}$ are the intensities of turbulence for the other two components.

There are two different systems of hydrodynamics used to specify turbulent motions. In the Eulerian system, the velocities at all positions in the flow are specified at a given instant. In the Lagrangian system, the velocities of a given particle or parcel are considered at different times as the particle moves in the flow.

A Theories of Turbulence

1 Prandtl's Mixing Length Theory

According to this theory, the mean path of an eddy, over which the eddy is maintained, is the mixing length. The mixing length is thus analogous to the mean free path of molecules. This theory implies a discontinuous motion of the atmosphere, but provided a way in which momentum, heat, and matter could be considered transferred according to the respective gradients of these quantities. (See Sutton, 1953;

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Pai, 1957; Pasquill, 1962). Variations of the mixing length theory were set fourth by Taylor 1915 and von Kármán.

2. Statistical Theory of Turbulence

The first representation of the atmosphere's motion as varying continuously is due to G.I. Taylor (1921), who considered the movement of a given particle with time (Lagrangian system). This was followed by a series of papers (Taylor, 1935) describing turbulence in an Eulerian frame of reference. Something about the size of eddies could be determined by consideration of the variation in velocity at a given time between two given points. The velocities at the two points would be more nearly the same for large eddies, than for small ones (Figure 2).

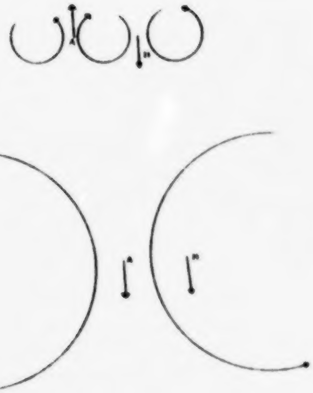

Figure 2. Comparison of Velocities at Two Points for Two Different Sizes of Eddies

a Space correlation coefficient

A statistical expression of the relation of the velocities at these two points can be obtained by using the space correlation coefficient. This measures the closeness of the relationship numerically. The correlation coefficient may vary between + 1 and - 1 being + 1 if there is a perfect relation, -1 if there is a perfect inverse relation, (i.e., as one velocity increases, the other decreases) and 0 if there is no relation. See Sutton (1961). Consider the points 1 and 2 that are a distance x apart. The correlation coefficient R(x) may be defined as

$$R(x) = \overline{u'_1 \quad u'_2} \Big/ \overline{u'_2}$$

where u'_1 is the eddy velocity at point 1, u'_2 is the eddy velocity at point 2, and $\overline{u'^2}$ is the mean eddy energy. It is assumed that R (x) and u'^2 are independent of position, i.e., the turbulence is homogeneous. As the distance, x, between the points increases, the correlation is expected to decrease. A graph of R(x) against x (correlogram) can be made if the correlations are known for x varying continuously. The rate of decrease of R(x) is related to the eddy sizes. A length, l, the scale of turbulence, may be defined by

$$l = \int_0^\infty R(x)\,dx$$

if this integral converges. Taylor considered l as the average size of eddies. Similarly, scales of turbulence in the y and z directions may be defined.

b Autocorrelation coefficient

A time correlation, coefficient, R(t), (an autocorrelation coefficient) may be defined by correlating eddy velocities measured at a point at different times. If the variations in wind speed at a point are caused by an unchanging pattern of turbulence passing, then

$$R(t) = R(x)$$

where $x = ut$

c Spectrum

In 1938, Taylor introduced the relation between the autocorrelation coefficient and the spectrum of turbulence. Where n is frequency (cycles per second) the portion of the total variance of frequencies between n and n + dn is $\overline{u'^2}\ F(n)\ dn$ where

$$\int_0^\infty F(n)\ dn = 1.$$

The curve formed by plotting F(n)or n F(n) against n is the energy spectrum or power spectrum. The quantity $\overline{u'^2}$ F(n) is the spectral density. Taylor showed that R(t), the autocorrelation coefficient, and F(n) are related by :

$$R(t) = \int_0^\infty F(n) \cos 2\pi nt\ dn \text{ and } F(n) = 4 \int_0^\infty R(t) \cos 2\pi nt\ dt$$

This provides a way of calculating the spectral density and of identifying the sizes (frequencies) of eddies that most greatly affect the kinetic energy.

B Isotropy

In the theoretical considerations of turbulence, it has been frequently assumed that the turbulence is isotropic. The turbulence is isotropic if the statistical properties are unaltered by rotation or reflection of the reference axes. Thus, the mean eddy energies $\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$ are equal. It was shown by von Kármán (1937) that if the turbulence is isotropic the spatial correlations R_x and R_y are different, but are related by $R_y = R_x + 1/2\ r \frac{dR_x}{dr}$

where r is the separation distance for both the x and y measurements. The correlation coefficient, R_x, along the wind direction is the longitudinal correlation coefficient, and R_y across wind is a transverse correlation coefficient. With isotropic turbulence, R_z is also a transverse correlation coefficient and is equal to R_y. There are also differences in the autocorrelations as well as the spatial correlations; the autocorrelation of the u' component is a longitudinal one whereas the autocorrelations of the v' and w' components are transverse. These differences must be considered in interpreting correlation coefficients, correlograms, or spectral functions.

Isotropy does not generally exist in the atmosphere, at least, not in the vicinity of the earth's surface which is the region of particular concern in air pollution. Kolmogoroff, in 1941, set forth the idea of local isotropy, i.e., if one considers the motion on a small enough scale, this motion is isotropic. His theory known as the similarity theory or theory of universal equilibrium indicates that most of the energy is contained in a particular group of eddies and that energy is continually passed to higher frequency eddies by inertial forces. There is also dissipation of energy by viscous forces mainly at the high frequencies. During the transfer process, the eddies lose their directional preference and a scale is reached where the turbulence is isotropic. See Pasquill (1962) and Batchelor (1950) for details of Kolmogoroff's theory.

C Sampling and Averaging Times

The atmospheric spectrum extends to large scales produced by the distrubances of the general circulation. Because of this, the statistical properties are highly dependent upon sampling time. If a sample is taken for a finite length of time, τ, the effects of the slow variations (low frequencies) will not be included. In most cases, the variances and autocorrelations do not reach constant or zero limiting values. As τ increases, so does the total variance. In addition, some of the fine structure (high frequencies) will be smoothed out since any observation must represent an average over some small time period, s. The inertia of the wind sensor will limit how small s can be. Thus, the sampling duration, τ, and the averaging time, s, have an important bearing on the values of the statistical properties. The fraction of the spectral density corresponding to each frequency is shown in Figure 3 for a sampling duration, τ, and for consecutive interval averaging times, s. Thus, only the portion of the spectrum that appears through this spectral window is known. Thus, for a sampling duration of $\tau = 1$ hour (3600 seconds) and averaging time $s = 1$ second, the fraction of the spectral density is 1.0 between 5.56×10^{-4} cycles per second ($2/\tau$) and 5×10^{-2} cycles per second ($0.05/s$). Thus, the fraction of the spectral density is 1.0 for the motions having a cycle of less than 30 minutes and more than 20 seconds.

D Statistical Properties of Turbulence

Turbulence is neither homogeneous (spatial variation) nor stationary (time variation) due to terrain and diurnal changes. Therefore, turbulence depends upon the particular place and time. Neuberger, et al., (1956) summarized the following 6 statistical properties of turbulence.

1. Turbulent energy is greatest in unstable air, least in stable air.
2. Vertical turbulent energy is somewhat smaller than horizontal turbulent energy.
3. When the atmosphere is stable, the turbulent variations are of high frequency with fluctuations on the order of a few seconds or fractions of seconds. During unstable conditions, longer period fluctuations on the order of minutes become important due to convection.
4. The scale of turbulence increases with height due to less damping by the ground. Fluctuations of longer periods become more important higher in the atmosphere.
5. Turbulent energy increases with increasing wind speed.
6. Turbulent energy is greater over rough ground than over smooth ground.

II DIFFUSION

In the Glossary of Meteorology, diffusion is defined as, "the exchange of fluid parcels (and hence, the transport of conservative properties) between regions in space, in the apparently random motions of a scale too small to be treated by the equations of motion".

A Transfer Theory

Transfer theory is the name given to one group of early mathematical expressions describing atmospheric diffusion. One such formulation still may be applied very near the ground, within one meter, and

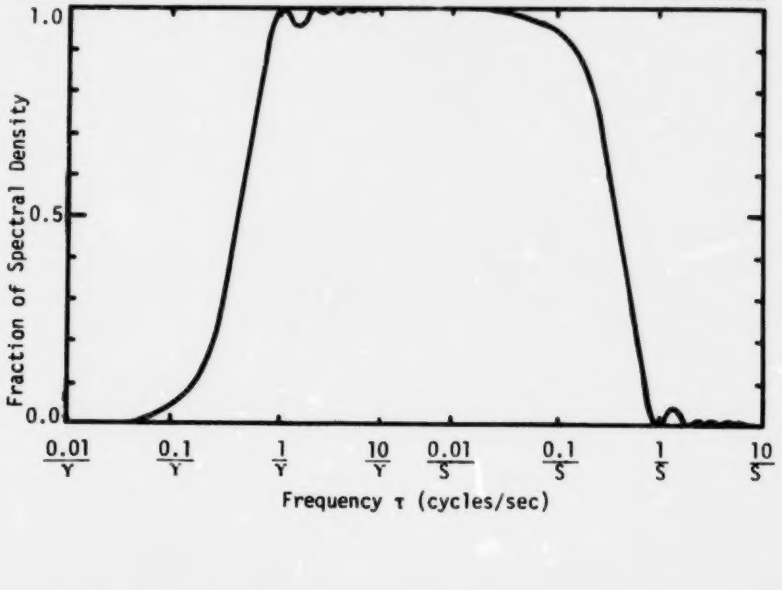

Figure 3.
The Spectral Window
Dependent on Sampling Time, τ,
and Averaging Time, s

another maybe used in regard to stratospheric-tropospheric exchange processes. These theories express a linear relation between the flux of a quantity and the gradient in the direction of the flux. For example:

$$F = -A \frac{\delta \bar{s}}{\delta n} \quad \text{and}$$

$$F = -\rho K \frac{\delta \bar{c}}{\delta n}$$

where F is the flux, s is the quantity per unit mass of the diffusing quantity, A is an exchange or austausch coefficient, and K is eddy diffusivity. These are equations for transfer theories. See Priestley et al., (1958).

The general diffusion equation resulting from transfer theory is:

$$\frac{d\chi}{dt} = \frac{\delta}{\delta x}\left(K_x \frac{\delta \chi}{\delta x}\right) + \frac{\delta}{\delta y}\left(K_y \frac{\delta \chi}{\delta y}\right) + \frac{\delta}{\delta z}\left(K_z \frac{\delta \chi}{\delta z}\right)$$

If $K_x = K_y = K_z$ = constant in the above equation, the resulting diffusion is termed "Fickian" after Albert Fick, a German physiologist of the mid 1800's. Frequently, this equation has been used with the K's, especially K_z, varying. One form of the equation for the continuous cross-wind line source is:

$$\bar{u} \frac{\delta \chi}{\delta x} = \frac{\delta}{\delta z}\left(K_z \frac{\delta \chi}{\delta z}\right)$$

Solutions for this equation have been worked out by O. F. T. Roberts and also by F. B. Smith, (1957).

B Statistical Theory

G. I. Taylor, in 1921, indicated that the cross-wind position of a small parcel of air or a particle of negligible size and mass that is being transported by the atmosphere at the time, t, after release is given by:

$$y = \int_0^t v'(t)\, dt$$

where v′ are the instantaneous eddy velocities of the particle in the y direction. Therefore, these are Lagrangian eddy velocities. The position of one particle is of no particular interest, but rather some statistical property of the entire ensemble of particles.

If the turbulence is homogeneous and stationary, i.e., if the average properties are uniform in space and steady in time, then:

$$\sigma_y^2 = 2\,\overline{v'^2} \int_0^T \int_0^t R(\xi)\, d\xi\, dt$$

where σ_y is the standard deviation of the particle in time T, $\overline{v'^2}$ is the mean square eddy velocity of the particle, and R (ξ) is the Lagrangian correlation coefficient between the velocity of the particle at t and at t + ξ. For small time, T, the Lagrangian autocorrelation R(ξ) is approximately 1.0 so that

$$\sigma_y^2 = v'^2 \quad T^2 \quad \text{(for small T)}$$

The spread is linear. For large T, R(ξ) is approximately zero so that

$$\sigma_y^2 = 2\left[\int_0^t R(\xi)\, d\xi\right] \overline{v'^2}\, T$$

(for large T)

The spread is parabolic and the term in the brackets is a constant time scale of turbulence. It is uncertain as to just what may be considered small T and large T. The indication is that one must know the form of the Lagrangian correlogram or spectrum in order to determine the diffusion.

Measuring Lagrangian properties of the atmosphere is extremely difficult.

Sutton in 1934, suggested a form for the Lagrangian autocorrelation:

$$R(\xi) = \left(\frac{\nu}{\nu + \overline{w^2}\,\xi} \right)^n$$

where ν is the kinematic viscosity of air.

This results in:

$$\sigma_y^2 = \tfrac{1}{2}\, C_y^2\, (\bar{u}\,T)^{2-n}$$

where

$$C_y^2 = \frac{4\,\nu^n}{(1-n)\,(2-n)\,\bar{u}^n} \left(\frac{\overline{v^2}}{\bar{v}^2} \right)^{1-n}$$

Sutton assumed a Gaussian distribution of concentrations in the diffusing cloud and that the wind is constant with height. See Sutton (1953).

C Relation of Lagrangian to Eulerian Statistics

Another approach to obtaining estimates of Lagrangian statistics may be by relating the Lagrangian correlogram or spectrum to the Eulerian properties as measured at a fixed point. Since accurate measurement of wind velocities may be made at a fixed point, this approach may be most feasible. Michelsen (1955) in wind tunnel experiments found a relation between the Eulerian and Lagrangian correlograms:

$$R(x) = \frac{1}{B^2}\, R(\xi)$$

when

$$\xi = \frac{x}{B\,(\overline{v^2})^{1/2}}$$

This showed that the Lagrangian correlogram falls off more slowly than the corresponding Eulerian value. This certainly seems reasonable since the Lagrangian measurement is the velocity of particles moving in eddies which are being transported according to the flow, whereas the Eulerian measurements are the velocities measured at a fixed point of eddies moving past that point according to the mean flow. Hay and Pasquill (1957) came to the conclusion that also in the atmosphere the Lagrangian correlation decreased more slowly than the autocorrelation at a fixed point. They (Hay and Pasquill, 1959) assumed the relation:

$$R_L(\xi) = R_E(t) \quad \text{when} \quad \xi = \beta t$$

the L referring to Lagrangian and E to Eulerian. The resulting relation between spectral densities is:

$$n\,F_L(n) = \beta\, n\, F_E(\beta n)$$

The assumed relations between the Eulerian and Lagrangian correlograms and spectra are shown in Figure 4.

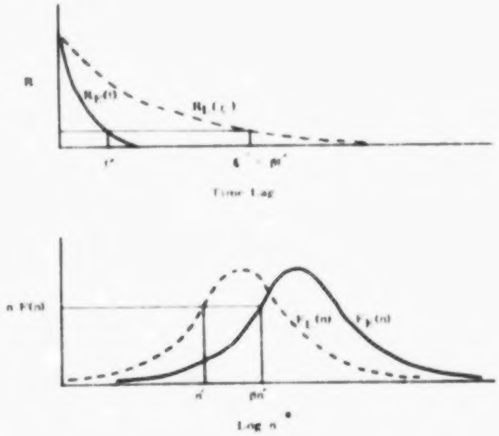

Figure 4. Hypothetical Scale Relation Between Lagrangian and Eulerian (fixed point) Correlograms (above) and Spectra (below) (From Pasquill, 1962)

The principal result of this is that the dispersion of particles in the atmosphere may be approximated by averaging the eddy velocity over time intervals of T/β over the period of release, τ, where T is the time of travel. Numerous field experiments to test this possibility are being made. See Pasquill (1961, 1962).

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THE GENERALIZED GAUSSIAN DIFFUSION EQUATION

The normal or Gaussian frequency curve is given by:

$$C(x) = \frac{1}{(2\pi)^{1/2}\sigma} \exp - \frac{(x - \bar{x})^2}{2\sigma^2} \qquad (1)$$

Where C is the probability density function, $\bar{x}$ is the mean and σ is the standard deviation. $(2\pi)^{1/2}$ makes the area under the curve from $x = -\infty$ to $x = +\infty$ equal to 1. See Figure 1.

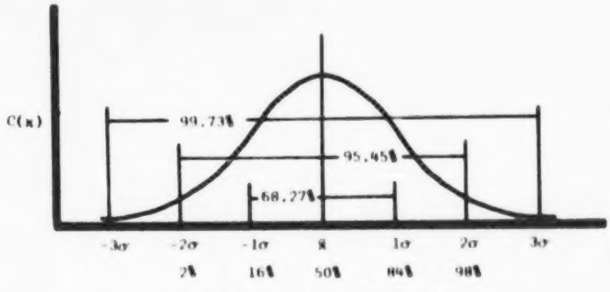

Figure 1. Normal Frequency Curve

Note: $\exp(-a/b) = e^{-\frac{a}{b}}$ where e is the mathematical constant approximately equal to 2.7183.

When a distribution is binormal in the two dimensions x and y the probability density function is:

$$C(x, y) = \frac{1}{2\pi\sigma_x\sigma_y}$$

$$\exp - \frac{1}{2}\left[\frac{(x - \bar{x})^2}{\sigma_x^2} + \frac{(y - \bar{y})^2}{\sigma_y^2}\right] \qquad (2)$$

If there is a continuous emission, Q, of gas or aerosols from a point, H, above the ground, define a 3 dimensional coordinate system so that the origin is on the ground beneath the point of emission, x is in the direction of the mean wind, $\bar{u}$, y is crosswind and z is vertical.

Assume that the diffusion in the crosswind and vertical dimensions will occur in a Gaussian manner, that the pollution will move downwind with the mean speed of the wind, and that the diffusion in the downwind direction is negligible compared with the transport.

The concentration, C, at any point (x, y, z) can be written as:

$$\frac{C(x, y, z)\,\bar{u}}{Q} = \frac{1}{2\pi\sigma_y\sigma_z}$$

$$\exp - \frac{1}{2}\left[\frac{y^2}{\sigma_y^2} + \frac{(z - H)^2}{\sigma_z^2}\right] \qquad (3)$$

Here $\bar{y}$ is assumed 0, and $\bar{z}$ assumed to be H. In this equation C has units of mass per volume, $\bar{u}$, velocity or length per time; Q, mass per time; σ_y and σ_z length; and y, z, and H, length.

Because diffusion in the z direction is bounded by the earth's surface, equation 3 cannot be strictly used. If it can be assumed that the ground acts as a perfect reflector, this has the effect of assuming a source at z = H and a virtual "image" source at z = -H then

$$\frac{C(x, y, z)\,\bar{u}}{Q} = \frac{1}{2\pi\sigma_y\sigma_z}\left[\exp \frac{-y^2}{2\sigma_y^2}\right]$$

$$\left[\exp - \frac{(z - H)^2}{2\sigma_z^2} + \exp - \frac{(z + H)^2}{2\sigma_z^2}\right] \qquad (4)$$

This is the generalized diffusion equation. We cannot expect to obtain instantaneous concentrations from this equation, but concentrations averaged over at least a few minutes time. There are several reasons why one may expect this equation to be valid for the atmosphere. This obeys the equation of continuity, i.e., the conservation of mass. The mass Q/1 second is found between any two planes perpendicular to the x axis at a distance $\bar{u}$/1 second part. Secondly, diffusion is a random process and the distribution of material from such motion may be expected to be in some statistical form; in this case, according to the Gaussian curve. There is one theoretical reason why one would not expect this equation to apply. Diffusion can only occur at a finite speed, i.e., the concentration of released material should drop at zero at some distance from the x axis because it has not diffused to this point. Assuming a Guassian distribution assumes the material to be spread from $-\infty$ to $+\infty$ crosswind. This is not of practical importance, however, as the Gaussian distribution drops off extremely rapidly within a few σ crosswind. One practical limitation is that the Gaussian distribution does not allow for any wind shear in the surface layer.

Interest is generally focused upon ground level concentrations, i.e., C(x, y, 0). Substituting z = 0 in (4) yields:

$$\frac{C(x,y,0)\,\bar{u}}{Q} = \frac{1}{\pi\sigma_y\sigma_z}\exp\left[-\frac{y^2}{2\sigma_y^2}-\frac{H^2}{2\sigma_z^2}\right] \qquad (5)$$

It will be noted that the 2 in the denominator in (4) is eliminated in (5) because of the 2 resulting from $2\exp-\frac{H^2}{2\sigma_z^2}$ occurring in the numerator.

If the source is at ground level, H = O, there is further simplification. Similarly, if one is interested only in centerline concentrations (directly downwind) then y = 0, and equation (5) may again be simplified.

This, (5), is the basic equation for calculating the ground level concentration from a continuous point source. The usual units for the variables are:

C (x, y, 0)	gms/m^3
$\bar{u}$	m/sec
Q	gms/sec
σ_y, σ_z, y, H,	meters

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ATMOSPHERIC DIFFUSION COMPUTATIONS

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J. L. Dicke[**]

With the increase in concern for air pollution both from conventional and radioactive sources, the need for determining the transport and diffusion of these pollutants in the atmosphere has become more pressing.

Pasquill (1961, 1962) of the British Meteorological Office devised a method of computing dispersion from an elevated or ground-level source in terms of the height and width of the plume of airborne material based on diffusion measurements made during Project Prairie Grass (Cramer et al., 1958) and other diffusion studies. This method was also published by Meade (1960). Gifford (1961) has transformed values of Pasquill's parameters of height and width to the standard deviations of plume concentration distribution in the vertical, σ_z, and horizontal, σ_y.

DIFFUSION EQUATION

Assuming that the plume has a Gaussian distribution in both the horizontal and vertical dimensions with standard deviations of plume concentration distribution in the vertical and horizontal of σ_z and σ_y respectively, the mean wind speed affecting the plume is $\bar{u}$, the height of emission is H, the crosswind distance from the plume centerline is y, the source strength is Q, and total reflection of the plume takes place at the earth's surface, the concentration at ground-level is given by:

$$C = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp - \frac{H^2}{2\sigma_z^2} \exp - \frac{y^2}{2\sigma_y^2} \qquad (1)$$

Any consistent set of units may be used. The most common is:

C	grams or curies/m^3
Q	grams or curies/sec
$\bar{u}$	meters/sec
σ_y	meters
σ_z	meters
H	meters
y	meters

The values of σ_y and σ_z must be in terms of a downwind distance, x. The computation of concentration, C, is therefore made for specific downwind distances. C is also the total dosage in gm-sec/m^3 or curies-sec/m^3 for the same distance for the passage of the entire plume if the total release is Q.

This equation is valid if diffusion in the downwind direction may be neglected. If the duration of release is equal to or greater than the travel time from the source to the location of interest, downwind diffusion may be assumed absent.

STABILITY

The values of both σ_y and σ_z will depend upon the turbulent structure of the atmosphere. If measures of horizontal and vertical motions of the air are made as with a bivane, the resulting records may be used to estimate σ_y and σ_z. (See Pasquill, 1961.) If wind fluctuation measurements are not available, estimates of σ_y and σ_z may be made by first estimating the stability of the atmosphere from wind measurements at the standard height of 10 meters, and estimates of net radiation (Pasquill, 1961). Stability categories (in six classes) are given in Table 1 in terms of insolation during daytime (radiation received from the sun) and amount of cloud cover at night. Strong insolation corresponds to a solar altitude (above the horizon) greater than 60° with clear skies, and slight insolation corresponds to a solar altitude from 15° to 35° with clear skies. Table 170, Solar Altitude and Azimuth in the Smithsonian Meteorological Tables (List, 1951) is of considerable aid in determining insolation. Cloudiness will generally decrease insolation and should be considered along with solar altitude in determining insolation. Insolation that would be strong with clear skies might be expected to be reduced to moderate with broken middle clouds and to slight with broken low clouds. Night refers to the period from one hour before sunset to one hour after sunrise. The neutral category, D, should be assumed for overcast conditions during day or night.

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ESTIMATION OF VERTICAL AND HORIZONTAL DISPERSION

Having determined the stability class from Table 1, the measures of diffusion in the vertical, σ_z, and in the horizontal, σ_y, may be estimated as a function of downwind distance from the source, x, using Figures 1 and 2. These values of σ_y and σ_z are valid for concentrations, C, averaged over a few minutes time and apply to open level country with no allowance made for turbulence due to buildings or topography. With very light winds on a clear night, the vertical spread may be less than the values for class F. Because of lack of quantitative knowledge and because a plume from a surface source is unlikely to have any definable travel, and elevated plumes will generally not reach the ground, no estimates are attempted for this case.

When conditions are such that the vertical structure of temperature indicates a definite limit to the vertical convection, particularly under unstable conditions, the σ_z should be allowed to increase only to $0.47\ h_1$ where h_1 is the limit of convection. At the distance x_1 where $\sigma_z = 0.47\ h_1$, the plume is still assumed to have a Gaussian vertical distribution. It can be assumed that by the time the plume travels twice this far, $2\ x_1$, the plume has become uniformly distributed between the earth's surface and the limit of convection. A value of σ_z equal to $0.8 h_1$ may be used and the exponential term dropped at distances equal to or greater than $2\ x_1$ and will give the concentration value computed by the equation equal to that from a plume uniformly distributed in the vertical.

ESTIMATION OF WIND SPEED

For mean wind speed, $\bar{u}$, the value measured at 10 meters height (surface wind) should be used for x up to about 1 km for surface sources or short stacks. For greater distances or elevated sources a mean speed through the vertical extent of the plume (about $2\ \sigma_z$) should be used. A speed midway between the surface and geostrophic speeds should be reasonable.

CALCULATION OF CENTERLINE CONCENTRATION FROM A GROUND LEVEL SOURCE

For most practical purposes it will be sufficient to calculate the centerline concentration for the distances 100 m, 1 km, 10 km, and 100 km and plot these against downwind distance x, on log/log graph paper for interpolation of concentrations for other distances. (For unstable or stable cases it is desirable to include several other distances). This may be done using the equation:

$$C_0 = \frac{Q}{\pi u \sigma_y \sigma_z} = \frac{3.18 \times 10^{-1} Q}{u \sigma_y \sigma_z} \qquad (2)$$

The zero subscript of C, concentration, indicates emission from a ground-level source. If there is a limit to convection, h, concentrations should also be calculated for distances x_1 and $2\ x_1$ using $\sigma_z = 0.47\ h_1$ and $\sigma_z = 0.8\ h_1$ respectively. Line segments connecting the calculated concentrations for the various distances will give a plot of concentration with distance.

CALCULATION OF GROUND-LEVEL CENTERLINE CONCENTRATION FROM AN ELEVATED SOURCE

Concentrations from an elevated source may be calculated from:

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \exp - \frac{H^2}{2 \sigma_z^2} \qquad (3)$$

where H is the effective height of the elevated source.

Values of $\exp - H^2/2\sigma_z^2$ are found in Table 3. A is the ratio of H/σ_z and B, the expressions in the body of the table, is the computed value of the exponential. The E represents x 10 to the power indicated by the following two digits. For example, if $A = 3.55$, the value of the exponential is 0.183×10^{-2}.

It is possible under light wind situations at night that the plume from an elevated source will remain aloft with no significant vertical diffusion, in which case the ground-level concentrations would be zero. Vertical spread can then be started at a downwind position corresponding to the wind speed and the estimated time for breakdown of the stable situation.

GRAPHS FOR ESTIMATION OF DIFFUSION

Hilsmeier and Gifford (1962) have presented graphs of relative concentration times wind speed (Cu/Q) below the plume centerline versus downwind distance for various stability classes. Figure 3 give Cu/Q as a function of x for a ground-level source whereas Figures 4-6 are for the indicated elevated sources.

CALCULATION OF OFF-AXIS CONCENTRATIONS

Off-axis concentrations may be calculated from equation 1, or by correcting ground-level centerline concentrations by the factor, $\exp - (y^2/2\sigma_y^2)$. This may be obtained from Table 3 for values of y/σ_y.

PLOTTING GROUND-LEVEL CONCENTRATION ISOPLETHS

It may be of interest in a given application to plot the position of the centerline of the plume and to determine areas covered by concentrations greater than a given magnitude. First the axial position of the plume must be known. The mean wind direction will determine the position. The surface wind may be used up to 1 km. Between 1 km and 100 km the average of the surface direction and the geostrophic direction backed by 10° will give a close approximation. The wind direction should be a mean through the vertical extent of the plume (about $2\sigma_z$).

In order to draw lines of equal concentration, it is easiest to locate on a log/log plot of centerline concentration against distance, the centerline concentration that is $\exp (y^2/2\sigma_y^2)$ times the concentration desired. The value of y, the off-axis distance, can then be found by knowing the y/σ_y value corresponding to the appropriate $\exp (y^2/2\sigma_y^2)$ (see Table 2) and the value of σ_y for this particular distance (from Figure 2). The position corresponding to the downwind distance and the off-axis distance can then be plotted. After a number of these points have been plotted, the concentration isopleth may be drawn and the area determined by using a planimeter. This assumes that the plume has a Gaussian distribution across wind. If there is a systematic veering or backing of the wind direction over a range that is large compared to the width of the trace, the plume may be assumed to be uniform in distribution across the width ($4.3\ \sigma_y$) of the plume and the concentration will be 0.58 of the calculated centerline concentration.

AREAS WITHIN CONCENTRATION ISOPLETHS

Figure 8 gives areas within ground-level concentration isopleths in terms of Cu/Q for a ground-level source for various stability categories (Hilsmeier and Gifford, 1962).

RAPID DETERMINATION OF MAXIMUM CONCENTRATION

The maximum concentration of pollutant will occur along the centerline of the plume, where y is zero, as indicated in equation 3 above. The distance downwind of the source at which the maximum concentration occurs at ground level is a function of effective source height and stability. Figure 7 is a nomogram from which the relative value of the maximum concentration can be determined given the stability and effective source height. If the relative value of that concentration is multiplied by Q/π, the maximum concentration for a specific set of conditions is obtained. The nomogram is designed for source strength expressed in grams/sec and wind speed in meters/sec.

ACCURACY OF COMPUTATIONS

The method will in general give only approximate estimates of concentrations, especially if wind fluctuation measurements are not available and estimates of dispersion are obtained from Figures 1 and 2. In the unstable and stable cases, errors of σ_z of several fold may occur for longer travel distances. There are cases where σ_z may be expected to be within a factor of 2. These are: 1) all stabilites for distances of travel of a few hundred meters in open country; 2) neutral to moderately unstable conditions for distances of a few kilometers; and 3) unstable conditions in the first 1000 meters above ground with a marked inversion thereafter for distances of 10 km or more. Uncertainties in the estimates of σ_y are in general less than those of σ_z except when the wind field is indefinite. In this case, the estimate of concentrations from the plume would be the same except that a wind range should be allowed for the direction of the plume, up to 360°. For extremes of stable and unstable conditions at distances between 50 and 100 km calculated concentrations may differ from true concentrations by an order of magnitude. For these distances under neutral conditions calculated concentrations should be within a factor of 5 of true concentrations.

EXERCISES WITH DIFFUSION PARAMETERS

1. What stability category would be most likely to occur when the wind is 6 - 8 m/sec?
2. If the sky is overcast - synonymous with cloudy - what would the stability category most likely be?
3. What would the stability category most likely be on a sunny April afternoon when the wind is 3 m/sec?
4. If the surface wind at night is 3 m/sec and there is 5/8 of low clouds, what is the most likely stability category?
5. What are σ_y and σ_z at 150 m from a source under B stability?
6. How much difference is there in σ_z at 5 km under D and F stability?
7. What is the value of σ_y at 20 km under C stability?
8. At 300 m how many times larger is σ_y under B stability than under D stability?
9. Under E stability how much greater is the horizontal dispersion factor than the vertical dispersion factor at 300m?
10. If the value of H/σ_z is 1.8 what is the value of exp - $1/2(H/\sigma_z)^2$?
11. The value of exp - $1/2(H/\sigma_z)^2$ is 2.2×10^{-3}. What is H/σ_z?
12. Under D stability and a wind speed of 5 m/sec, a plume is emitted at 100 m above the ground. What is the value of C/Q at 4 km?
13. What is the area enclosed by an isopleth whose Cu/Q value is 4×10^{-4} m^{-2} when the stability category is B?

TABLE 1. KEY TO STABILITY CATEGORIES

Surface Wind Speed (at 10 m) m/sec	Insolation			Night	
	Strong	Moderate	Slight	Thinly Overcast or ≥ 4/8 Low Cloud	≤ 3/8 Cloud
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

The neutral category, D, should be assumed for overcast conditions during day or night

TABLE 2

y/σ_y	$\exp(y^2/2\sigma_y^2)$
0	1.00
0.1	1.01
0.2	1.02
0.3	1.05
0.4	1.08
0.5	1.13
0.6	1.20
0.7	1.28
0.8	1.38
0.9	1.50
1.0	1.65
1.2	2.05
1.4	2.66
1.5	3.08
1.6	3.60
1.8	5.05
2.0	7.39
2.15	10
3.04	10^2
3.72	10^3
4.29	10^4
4.80	10^5

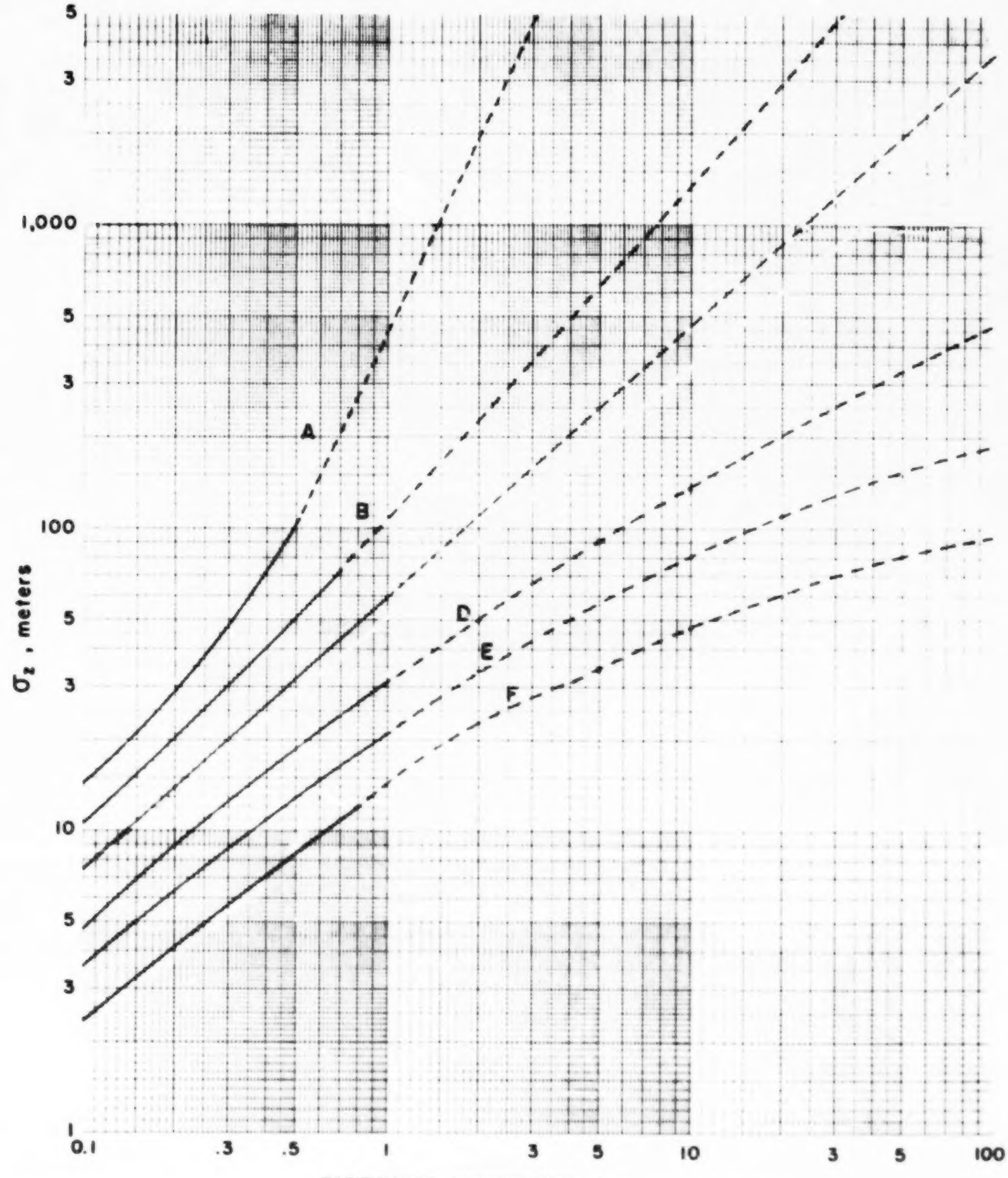


Figure 1

VERTICAL DISPERSION STANDARD DEVIATIONS

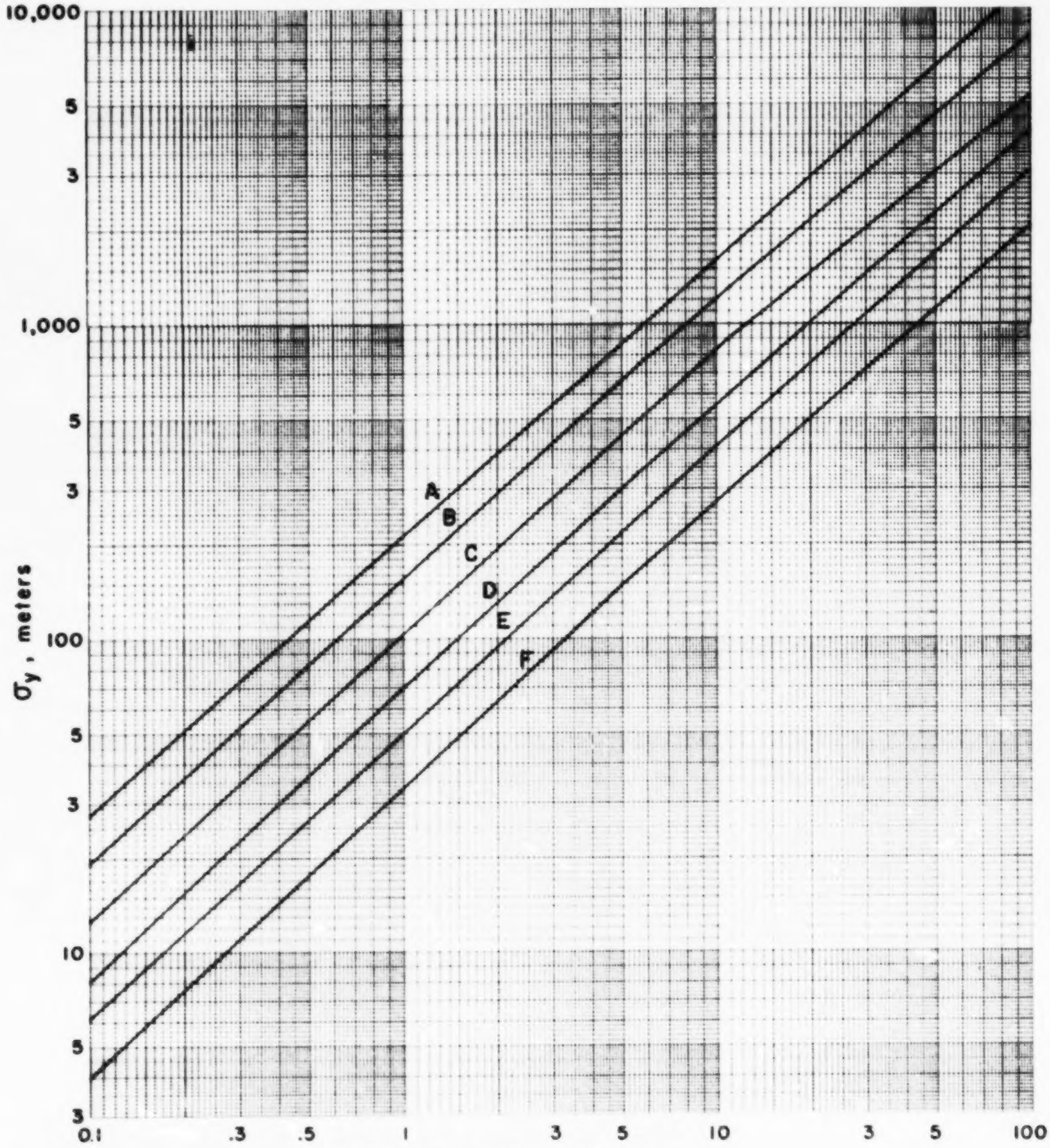


Figure 2

HORIZONTAL DISPERSION STANDARD DEVIATIONS

TABLE 3

$$B = \exp - \tfrac{1}{2}(A)^2$$

A	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.00	0.100E 01	0.100E 01	0.100E 01	0.100E 01	0.999E 00	0.999E 00	0.998E 00	0.998E 00	0.997E 00	0.996E 00
0.10	0.995E 00	0.994E 00	0.993E 00	0.992E 00	0.990E 00	0.989E 00	0.987E 00	0.986E 00	0.984E 00	0.982E 00
0.20	0.980E 00	0.978E 00	0.976E 00	0.974E 00	0.972E 00	0.969E 00	0.967E 00	0.964E 00	0.962E 00	0.959E 00
0.30	0.956E 00	0.953E 00	0.950E 00	0.947E 00	0.944E 00	0.941E 00	0.937E 00	0.934E 00	0.930E 00	0.927E 00
0.40	0.923E 00	0.919E 00	0.916E 00	0.912E 00	0.908E 00	0.904E 00	0.900E 00	0.895E 00	0.891E 00	0.887E 00
0.50	0.882E 00	0.878E 00	0.874E 00	0.869E 00	0.864E 00	0.860E 00	0.855E 00	0.850E 00	0.845E 00	0.840E 00
0.60	0.835E 00	0.830E 00	0.825E 00	0.820E 00	0.815E 00	0.810E 00	0.804E 00	0.799E 00	0.794E 00	0.788E 00
0.70	0.783E 00	0.777E 00	0.772E 00	0.766E 00	0.760E 00	0.755E 00	0.749E 00	0.743E 00	0.738E 00	0.732E 00
0.80	0.726E 00	0.720E 00	0.714E 00	0.709E 00	0.703E 00	0.697E 00	0.691E 00	0.685E 00	0.679E 00	0.673E 00
0.90	0.667E 00	0.661E 00	0.655E 00	0.649E 00	0.643E 00	0.637E 00	0.631E 00	0.625E 00	0.619E 00	0.613E 00
1.00	0.607E 00	0.600E 00	0.594E 00	0.588E 00	0.582E 00	0.576E 00	0.570E 00	0.564E 00	0.558E 00	0.552E 00
1.10	0.546E 00	0.540E 00	0.534E 00	0.528E 00	0.522E 00	0.516E 00	0.510E 00	0.504E 00	0.498E 00	0.493E 00
1.20	0.487E 00	0.481E 00	0.475E 00	0.469E 00	0.464E 00	0.458E 00	0.452E 00	0.446E 00	0.441E 00	0.435E 00
1.30	0.430E 00	0.424E 00	0.418E 00	0.413E 00	0.407E 00	0.402E 00	0.397E 00	0.391E 00	0.386E 00	0.381E 00
1.40	0.375E 00	0.370E 00	0.365E 00	0.360E 00	0.355E 00	0.350E 00	0.344E 00	0.339E 00	0.334E 00	0.330E 00
1.50	0.325E 00	0.320E 00	0.315E 00	0.310E 00	0.306E 00	0.301E 00	0.296E 00	0.292E 00	0.287E 00	0.283E 00
1.60	0.278E 00	0.274E 00	0.269E 00	0.265E 00	0.261E 00	0.256E 00	0.252E 00	0.248E 00	0.244E 00	0.240E 00
1.70	0.236E 00	0.232E 00	0.228E 00	0.224E 00	0.220E 00	0.216E 00	0.213E 00	0.209E 00	0.205E 00	0.201E 00
1.80	0.198E 00	0.194E 00	0.191E 00	0.187E 00	0.184E 00	0.181E 00	0.177E 00	0.174E 00	0.171E 00	0.168E 00
1.90	0.164E 00	0.161E 00	0.158E 00	0.155E 00	0.152E 00	0.149E 00	0.146E 00	0.144E 00	0.141E 00	0.138E 00
2.00	0.135E 00	0.133E 00	0.130E 00	0.127E 00	0.125E 00	0.122E 00	0.120E 00	0.117E 00	0.115E 00	0.113E 00
2.10	0.110E 00	0.108E 00	0.106E 00	0.103E 00	0.101E 00	0.991E-01	0.970E-01	0.949E-01	0.929E-01	0.909E-01
2.20	0.889E-01	0.870E-01	0.851E-01	0.832E-01	0.814E-01	0.796E-01	0.778E-01	0.760E-01	0.743E-01	0.727E-01
2.30	0.710E-01	0.694E-01	0.678E-01	0.662E-01	0.647E-01	0.632E-01	0.617E-01	0.603E-01	0.589E-01	0.575E-01
2.40	0.561E-01	0.548E-01	0.535E-01	0.522E-01	0.510E-01	0.497E-01	0.485E-01	0.473E-01	0.462E-01	0.450E-01
2.50	0.439E-01	0.428E-01	0.418E-01	0.407E-01	0.397E-01	0.387E-01	0.377E-01	0.368E-01	0.359E-01	0.349E-01
2.60	0.340E-01	0.332E-01	0.323E-01	0.315E-01	0.307E-01	0.299E-01	0.291E-01	0.283E-01	0.276E-01	0.268E-01
2.70	0.261E-01	0.254E-01	0.247E-01	0.241E-01	0.234E-01	0.228E-01	0.222E-01	0.216E-01	0.210E-01	0.204E-01
2.80	0.198E-01	0.193E-01	0.188E-01	0.182E-01	0.177E-01	0.172E-01	0.167E-01	0.163E-01	0.158E-01	0.154E-01
2.90	0.149E-01	0.145E-01	0.141E-01	0.137E-01	0.133E-01	0.129E-01	0.125E-01	0.121E-01	0.118E-01	0.114E-01
3.00	0.111E-01	0.108E-01	0.105E-01	0.101E-01	0.984E-02	0.955E-02	0.926E-02	0.898E-02	0.871E-02	0.845E-02
3.10	0.819E-02	0.794E-02	0.769E-02	0.746E-02	0.723E-02	0.700E-02	0.679E-02	0.658E-02	0.637E-02	0.617E-02
3.20	0.598E-02	0.579E-02	0.560E-02	0.543E-02	0.525E-02	0.509E-02	0.492E-02	0.477E-02	0.461E-02	0.446E-02
3.30	0.432E-02	0.418E-02	0.404E-02	0.391E-02	0.378E-02	0.366E-02	0.354E-02	0.342E-02	0.331E-02	0.320E-02
3.40	0.309E-02	0.299E-02	0.289E-02	0.279E-02	0.269E-02	0.260E-02	0.251E-02	0.243E-02	0.235E-02	0.227E-02
3.50	0.219E-02	0.211E-02	0.204E-02	0.197E-02	0.190E-02	0.183E-02	0.177E-02	0.171E-02	0.165E-02	0.159E-02
3.60	0.153E-02	0.148E-02	0.143E-02	0.138E-02	0.133E-02	0.128E-02	0.123E-02	0.119E-02	0.115E-02	0.110E-02
3.70	0.106E-02	0.103E-02	0.989E-03	0.952E-03	0.918E-03	0.884E-03	0.851E-03	0.820E-03	0.789E-03	0.760E-03
3.80	0.732E-03	0.704E-03	0.678E-03	0.653E-03	0.628E-03	0.604E-03	0.582E-03	0.560E-03	0.538E-03	0.518E-03
3.90	0.498E-03	0.479E-03	0.460E-03	0.443E-03	0.426E-03	0.409E-03	0.393E-03	0.378E-03	0.363E-03	0.349E-03
4.00	0.335E-03	0.322E-03	0.310E-03	0.297E-03	0.286E-03	0.274E-03	0.263E-03	0.253E-03	0.243E-03	0.233E-03
4.10	0.224E-03	0.215E-03	0.206E-03	0.198E-03	0.190E-03	0.182E-03	0.175E-03	0.168E-03	0.161E-03	0.154E-03
4.20	0.148E-03	0.142E-03	0.136E-03	0.130E-03	0.125E-03	0.120E-03	0.115E-03	0.110E-03	0.105E-03	0.101E-03
4.30	0.966E-04	0.925E-04	0.886E-04	0.849E-04	0.813E-04	0.778E-04	0.745E-04	0.713E-04	0.683E-04	0.653E-04
4.40	0.625E-04	0.598E-04	0.572E-04	0.548E-04	0.524E-04	0.501E-04	0.479E-04	0.458E-04	0.438E-04	0.419E-04
4.50	0.401E-04	0.383E-04	0.366E-04	0.350E-04	0.334E-04	0.320E-04	0.305E-04	0.292E-04	0.279E-04	0.266E-04
4.60	0.254E-04	0.243E-04	0.232E-04	0.221E-04	0.211E-04	0.202E-04	0.193E-04	0.184E-04	0.175E-04	0.167E-04
4.70	0.160E-04	0.152E-04	0.145E-04	0.139E-04	0.132E-04	0.126E-04	0.120E-04	0.115E-04	0.109E-04	0.104E-04
4.80	0.993E-05	0.946E-05	0.902E-05	0.859E-05	0.819E-05	0.780E-05	0.743E-05	0.708E-05	0.674E-05	0.642E-05
4.90	0.611E-05	0.582E-05	0.554E-05	0.528E-05	0.502E-05	0.478E-05	0.455E-05	0.433E-05	0.412E-05	0.392E-05

TABLE 3 Con't.

$$B = \exp - \tfrac{1}{2}(A)^2$$

A	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
5.00	0.373E-05	0.354E-05	0.337E-05	0.321E-05	0.305E-05	0.290E-05	0.276E-05	0.262E-05	0.249E-05	0.237E-05
5.10	0.225E-05	0.214E-05	0.203E-05	0.193E-05	0.183E-05	0.174E-05	0.165E-05	0.157E-05	0.149E-05	0.142E-05
5.20	0.136E-05	0.128E-05	0.121E-05	0.115E-05	0.109E-05	0.103E-05	0.982E-06	0.932E-06	0.884E-06	0.838E-06
5.30	0.795E-06	0.754E-06	0.715E-06	0.678E-06	0.643E-06	0.609E-06	0.577E-06	0.547E-06	0.519E-06	0.491E-06
5.40	0.466E-06	0.441E-06	0.418E-06	0.396E-06	0.375E-06	0.355E-06	0.336E-06	0.318E-06	0.301E-06	0.285E-06
5.50	0.270E-06	0.255E-06	0.242E-06	0.229E-06	0.216E-06	0.205E-06	0.194E-06	0.183E-06	0.173E-06	0.164E-06
5.60	0.155E-06	0.147E-06	0.139E-06	0.131E-06	0.124E-06	0.117E-06	0.111E-06	0.104E-06	0.987E-07	0.932E-07
5.70	0.881E-07	0.832E-07	0.786E-07	0.742E-07	0.701E-07	0.662E-07	0.625E-07	0.590E-07	0.556E-07	0.525E-07
5.80	0.496E-07	0.468E-07	0.441E-07	0.416E-07	0.393E-07	0.370E-07	0.349E-07	0.329E-07	0.311E-07	0.293E-07
5.90	0.276E-07	0.260E-07	0.245E-07	0.231E-07	0.218E-07	0.205E-07	0.193E-07	0.182E-07	0.172E-07	0.162E-07
6.00	0.152E-07	0.143E-07	0.135E-07	0.127E-07	0.120E-07	0.113E-07	0.106E-07	0.998E-08	0.939E-08	0.884E-08
6.10	0.832E-08	0.782E-08	0.736E-08	0.692E-08	0.651E-08	0.612E-08	0.576E-08	0.541E-08	0.509E-08	0.478E-08
6.20	0.450E-08	0.423E-08	0.397E-08	0.373E-08	0.351E-08	0.329E-08	0.309E-08	0.291E-08	0.273E-08	0.256E-08
6.30	0.241E-08	0.226E-08	0.212E-08	0.199E-08	0.187E-08	0.175E-08	0.165E-08	0.154E-08	0.145E-08	0.136E-08
6.40	0.128E-08	0.120E-08	0.112E-08	0.105E-08	0.987E-09	0.925E-09	0.867E-09	0.813E-09	0.762E-09	0.714E-09
6.50	0.669E-09	0.627E-09	0.587E-09	0.550E-09	0.516E-09	0.483E-09	0.452E-09	0.424E-09	0.397E-09	0.371E-09
6.60	0.348E-09	0.325E-09	0.305E-09	0.285E-09	0.267E-09	0.250E-09	0.234E-09	0.218E-09	0.204E-09	0.191E-09
6.70	0.179E-09	0.167E-09	0.156E-09	0.146E-09	0.137E-09	0.128E-09	0.119E-09	0.112E-09	0.104E-09	0.974E-10
6.80	0.910E-10	0.850E-10	0.794E-10	0.742E-10	0.693E-10	0.647E-10	0.604E-10	0.564E-10	0.527E-10	0.492E-10
6.90	0.459E-10	0.428E-10	0.400E-10	0.373E-10	0.348E-10	0.325E-10	0.303E-10	0.282E-10	0.263E-10	0.246E-10
7.00	0.229E-10	0.213E-10	0.199E-10	0.186E-10	0.173E-10	0.161E-10	0.150E-10	0.140E-10	0.130E-10	0.121E-10
7.10	0.113E-10	0.105E-10	0.981E-11	0.914E-11	0.851E-11	0.792E-11	0.738E-11	0.687E-11	0.639E-11	0.595E-11
7.20	0.553E-11	0.515E-11	0.479E-11	0.446E-11	0.415E-11	0.386E-11	0.359E-11	0.334E-11	0.310E-11	0.288E-11
7.30	0.268E-11	0.249E-11	0.232E-11	0.215E-11	0.200E-11	0.186E-11	0.173E-11	0.160E-11	0.149E-11	0.138E-11
7.40	0.129E-11	0.119E-11	0.111E-11	0.103E-11	0.955E-12	0.887E-12	0.823E-12	0.764E-12	0.709E-12	0.658E-12
7.50	0.610E-12	0.566E-12	0.525E-12	0.487E-12	0.452E-12	0.419E-12	0.388E-12	0.360E-12	0.334E-12	0.309E-12
7.60	0.287E-12	0.266E-12	0.246E-12	0.228E-12	0.211E-12	0.196E-12	0.181E-12	0.168E-12	0.156E-12	0.144E-12
7.70	0.133E-12	0.124E-12	0.114E-12	0.106E-12	0.980E-13	0.907E-13	0.839E-13	0.777E-13	0.718E-13	0.665E-13
7.80	0.615E-13	0.569E-13	0.526E-13	0.486E-13	0.450E-13	0.416E-13	0.384E-13	0.355E-13	0.328E-13	0.303E-13
7.90	0.280E-13	0.259E-13	0.239E-13	0.221E-13	0.204E-13	0.189E-13	0.174E-13	0.161E-13	0.149E-13	0.137E-13
8.00	0.127E-13	0.117E-13	0.108E-13	0.996E-14	0.919E-14	0.848E-14	0.782E-14	0.722E-14	0.666E-14	0.614E-14
8.10	0.566E-14	0.522E-14	0.481E-14	0.444E-14	0.409E-14	0.377E-14	0.348E-14	0.320E-14	0.295E-14	0.272E-14
8.20	0.251E-14	0.231E-14	0.213E-14	0.196E-14	0.180E-14	0.166E-14	0.153E-14	0.141E-14	0.130E-14	0.119E-14
8.30	0.110E-14	0.101E-14	0.930E-15	0.856E-15	0.787E-15	0.724E-15	0.666E-15	0.613E-15	0.564E-15	0.518E-15
8.40	0.477E-15	0.438E-15	0.403E-15	0.370E-15	0.340E-15	0.313E-15	0.287E-15	0.264E-15	0.243E-15	0.223E-15
8.50	0.205E-15	0.188E-15	0.173E-15	0.159E-15	0.146E-15	0.134E-15	0.123E-15	0.113E-15	0.103E-15	0.949E-16
8.60	0.871E-16	0.799E-16	0.733E-16	0.672E-16	0.617E-16	0.566E-16	0.519E-16	0.476E-16	0.436E-16	0.400E-16
8.70	0.367E-16	0.336E-16	0.308E-16	0.282E-16	0.259E-16	0.237E-16	0.217E-16	0.199E-16	0.182E-16	0.167E-16
8.80	0.153E-16	0.140E-16	0.128E-16	0.117E-16	0.107E-16	0.983E-17	0.900E-17	0.823E-17	0.753E-17	0.689E-17
8.90	0.631E-17	0.577E-17	0.528E-17	0.483E-17	0.441E-17	0.404E-17	0.369E-17	0.337E-17	0.308E-17	0.282E-17
9.00	0.258E-17	0.235E-17	0.215E-17	0.197E-17	0.180E-17	0.164E-17	0.150E-17	0.137E-17	0.125E-17	0.114E-17
9.10	0.104E-17	0.952E-18	0.869E-18	0.793E-18	0.724E-18	0.661E-18	0.603E-18	0.550E-18	0.502E-18	0.458E-18
9.20	0.418E-18	0.381E-18	0.347E-18	0.317E-18	0.289E-18	0.263E-18	0.240E-18	0.219E-18	0.199E-18	0.182E-18
9.30	0.166E-18	0.151E-18	0.137E-18	0.125E-18	0.114E-18	0.104E-18	0.946E-19	0.861E-19	0.784E-19	0.714E-19
9.40	0.650E-19	0.592E-19	0.538E-19	0.490E-19	0.446E-19	0.406E-19	0.369E-19	0.336E-19	0.305E-19	0.278E-19
9.50	0.253E-19	0.230E-19	0.209E-19	0.190E-19	0.173E-19	0.157E-19	0.143E-19	0.130E-19	0.118E-19	0.107E-19
9.60	0.972E-20	0.883E-20	0.802E-20	0.729E-20	0.662E-20	0.601E-20	0.545E-20	0.495E-20	0.450E-20	0.408E-20
9.70	0.370E-20	0.336E-20	0.305E-20	0.277E-20	0.251E-20	0.228E-20	0.207E-20	0.187E-20	0.170E-20	0.154E-20
9.80	0.140E-20	0.127E-20	0.115E-20	0.104E-20	0.943E-21	0.855E-21	0.775E-21	0.702E-21	0.636E-21	0.576E-21
9.90	0.522E-21	0.472E-21	0.428E-21	0.387E-21	0.351E-21	0.318E-21	0.288E-21	0.260E-21	0.236E-21	0.213E-21

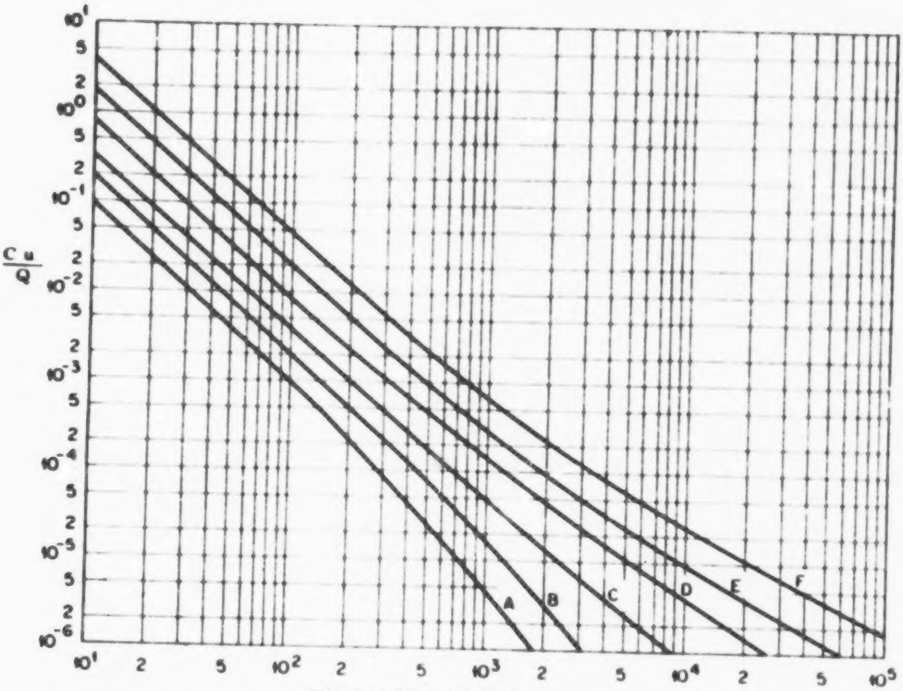
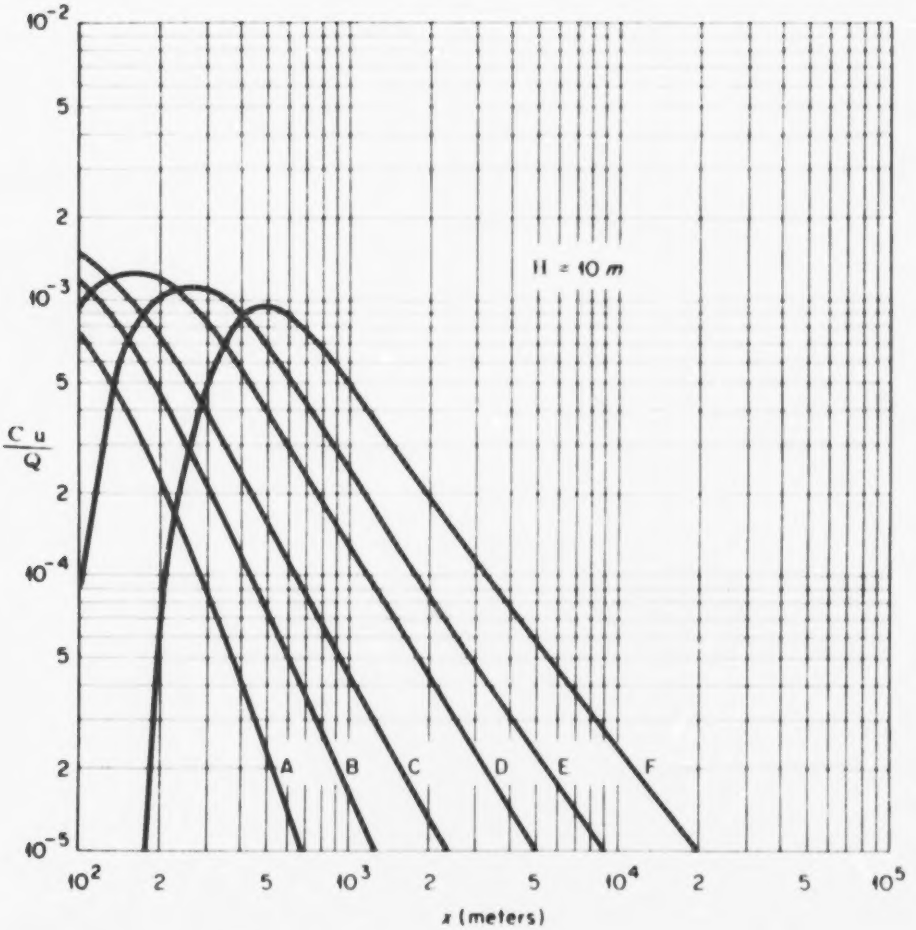


Figure 3 x (meters)



10⁻²
5
2
10⁻³
5
2
10⁻⁴
5
2
10⁻⁵
Cu/Q
H = 10 m
A
B
C
D
E
F
10²
2
5
10³
2
5
10⁴
2
5
10⁵
x (meters)

Figure 4

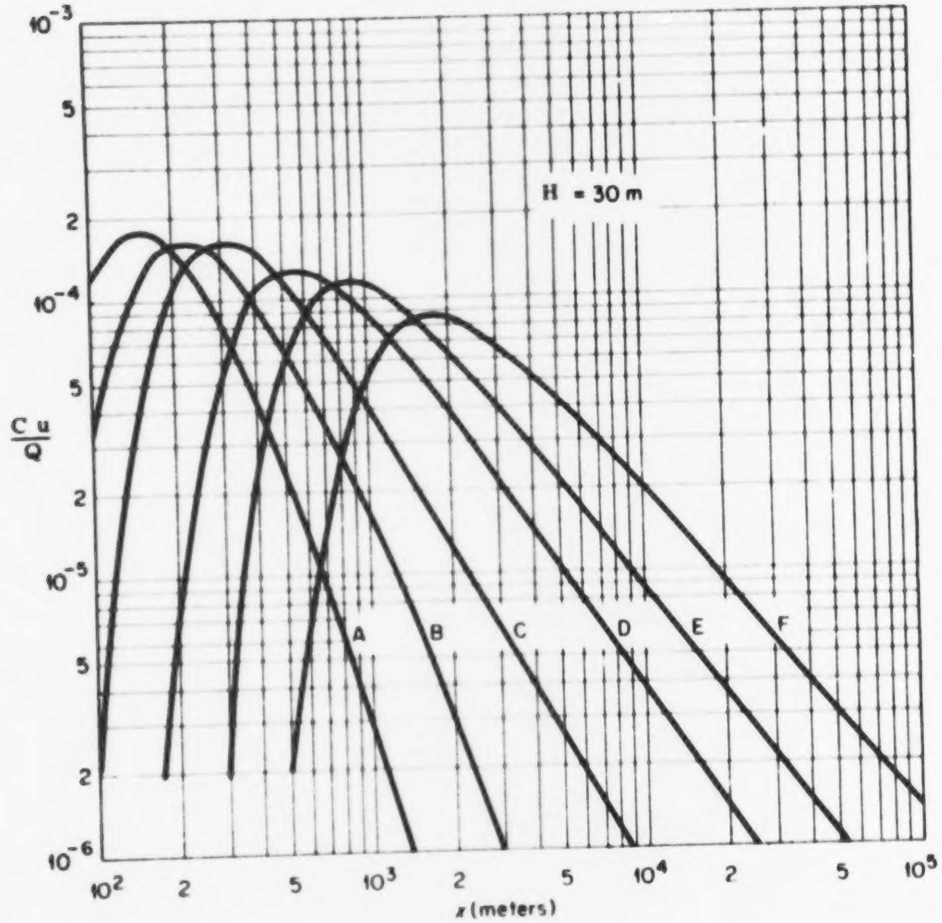

10^{-3}
5
2
10^{-4}
5
$\frac{C\,u}{Q}$
2
10^{-5}
5
2
10^{-6}
H = 30 m
A
B
C
D
E
F
10^2
2
5
10^3
2
5
10^4
2
5
10^5
x (meters)

Figure 5

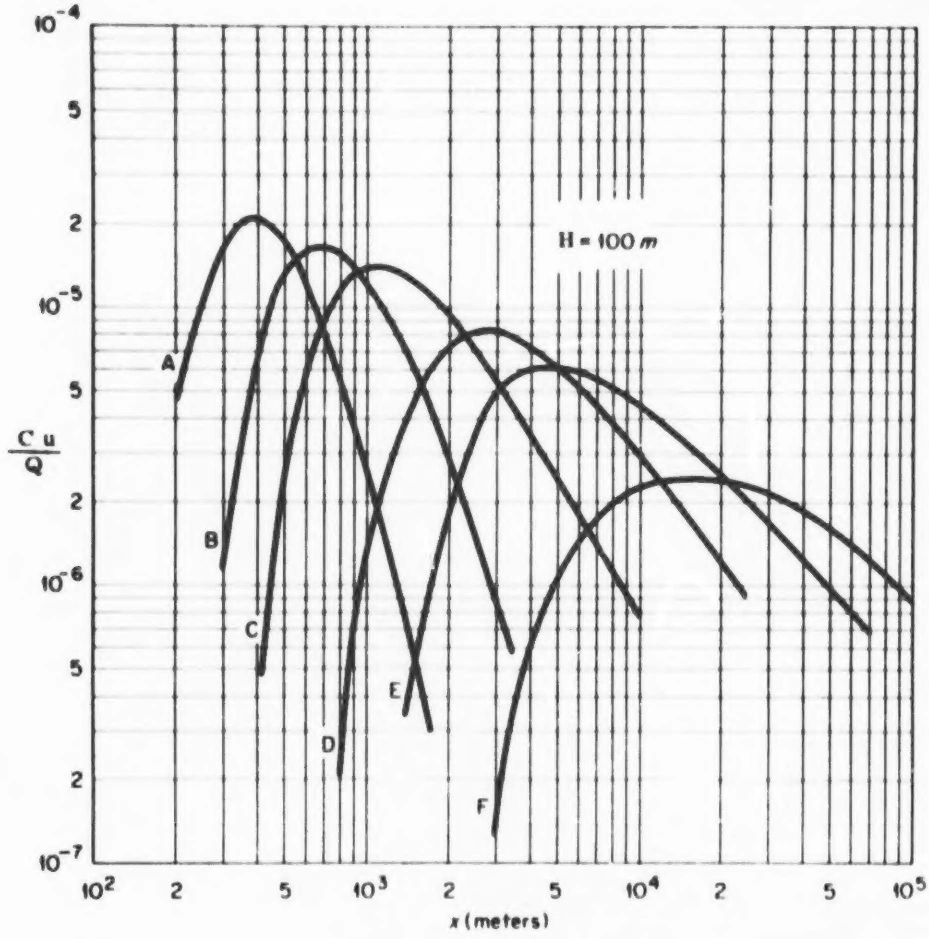

H = 100 m
A
B
C
D
E
F
$\frac{Cu}{Q}$
10^{-4}
5
2
10^{-5}
5
2
10^{-6}
5
2
10^{-7}
10^{2}
2
5
10^{3}
2
5
10^{4}
2
5
10^{5}
x (meters)

Figure 6

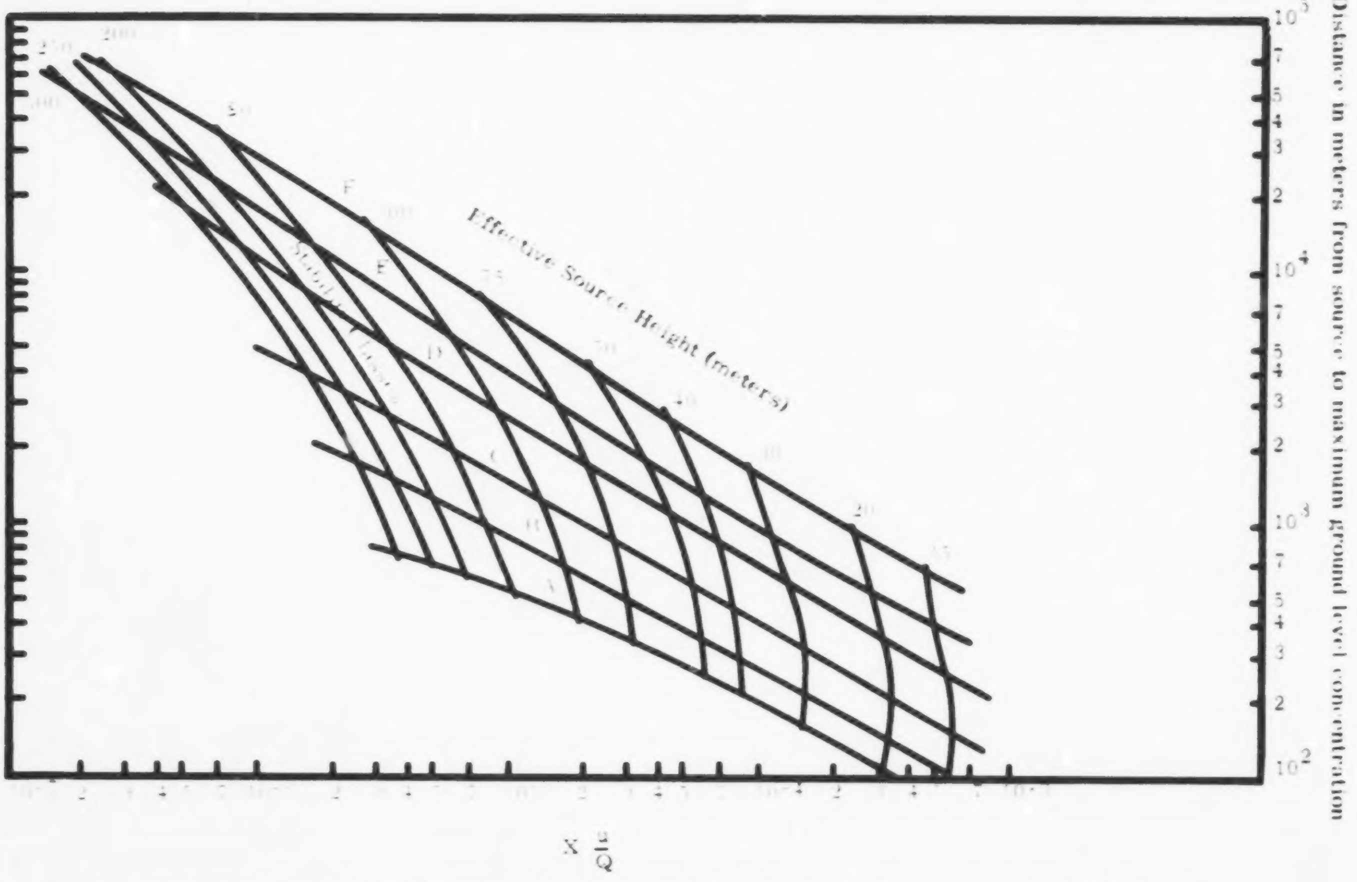


Figure 7. DISTANCE FROM SOURCE AND RELATIVE VALUE OF MAXIMUM CONCENTRATIONS FOR VARIOUS SOURCE HEIGHTS AND STABILITY CLASSES

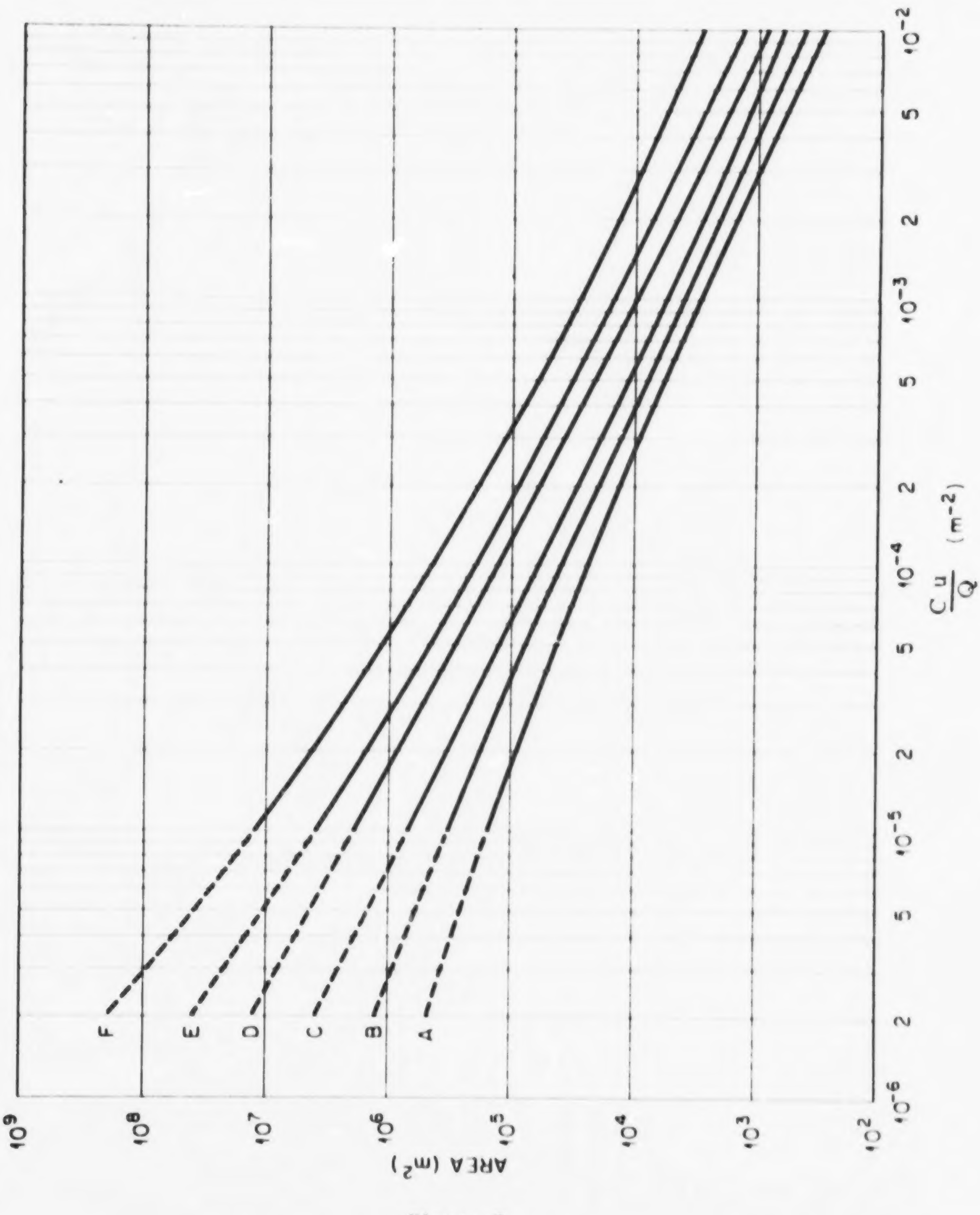

F
E
D
C
B
A
AREA (m²)
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
Cu/Q (m⁻²)
10⁻⁶
2
5
10⁻⁵
2
5
10⁻⁴
2
5
10⁻³
2
5
10⁻²

Figure 8

EXAMPLE DIFFUSION COMPUTATIONS

I A power plant burns 10 tons per hour of 3% sulfur coal releasing the effluent from a single stack. On a sunny summer afternoon the wind speed at 10 meters is 4 m/sec from the northeast. The morning radiosonde run in the vicinity has indicated that a frontal inversion aloft will limit the convection to 1500 meters. The 1200 meter wind is from 30° at 5 m/sec. The effective height of emission is 150 meters. What is the maximum concentration and where does it occur?

Solution: On a sunny summer afternoon the isolation should be strong. From Table 1, strong isolation and 4 m/sec winds yield B class stability. The amount of sulfur burned is:

$$\text{Sulfur} = \frac{10 \text{ tons}}{\text{hour}} \times \frac{2000 \text{ lbs.}}{\text{ton}} \times 0.03 \text{ sulfur} = 600 \text{ lbs/hr.}$$

Sulfur has a molecular weight of 32 and combines with O_2 with a molecular weight of 32; therefore, for every pound of sulfur burned, there results two pounds of SO_2.

$$Q = \frac{2\ SO_2}{S} \times \frac{600 \text{ lbs. S}}{\text{hr.}} \times \frac{453.6 \text{ gms/lb.}}{3600 \text{ sec/hr}}$$

$$= 151 \text{ gms. } SO_2/\text{sec.}$$

The maximum concentration may be found by using Figure 7. Given stability class B and effective source height of 150 m., enter the nomogram and read the $C\frac{u}{Q}$ value of 8×10^{-6} from the abscissa. Solve for the maximum concentration, $C_{(max)}$, using the wind speed, u, of 4 m/sec and the source strength, Q, of 151 gms. SO_2/sec.

$$C_{(max)} = 8 \times 10^{-6} \times \frac{151 \text{ gms/sec}}{4 \text{ m/sec}} = 3 \times 10^{-4} \text{ gm/m}^3$$

The distance from the power plant at which the maximum concentration occurs under these meteorological condition can be read from the ordinate in Figure 7. The distance is 1000m.

II Using the conditions in the above problem, draw a graph of centerline sulfur dioxide concentrations beneath the plume with distance from 100 meters to 100 km.

Solution: Since the frontal inversion limits the convection to h_l = 1500 meters, the distance where $\sigma_z = 0.47\ h_l = 700$ meters is $x_l = 5.5$ km. At distances equal to or greater than $2\ x_l = 11.0$ km, $\sigma_z = 0.8\ h_l = 1200$ meters. Equation 3 is used to find concentration as a function of distance:

$$C = \frac{151}{\pi\, u\, \sigma_y\, \sigma_z} \exp - \frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2$$

In this case H = 150 meters. Solutions for this equation are given in Table 4. The values of concentration in Table 4 are plotted against distance in Figure 9.

III Draw a graph of concentration versus cross-wind distance at a downwind distance of 800 meters for the conditions of problem 1 and 2.

Solution: From problem 2, the centerline concentration at 800 meters is 2.9×10^{-4} gms / m^3. To determine the concentrations at distances y from the x axis the centerline concentration must be multiplied by the factor $\exp - \frac{1}{2}(y/\sigma_y)^2$. σ_y = 120 meters at x = 800 meters. Values for this computation are given in Table 5.

TABLE 4

Col. a	Col. b	Col. c	Col. d	Col. e	Col. f	Col. g
x (km)	u (m/sec)	σ_y m	σ_z m	H/σ_z	$\exp - \frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2$	C gms/m^3
0.3	4	47	30	5.0	3×10^{-6}	2.6×10^{-8}
0.5	4	77	53	2.83	1.7×10^{-2}	5.0×10^{-5}
0.8	4	120	93	1.61	0.27	2.9×10^{-4}
1	4	150	125	1.20	0.48	3.1×10^{-4}
2.8	4.5	375	700	0.21	0.98	4.0×10^{-5}
5.6	4.5	700	1200	0.125	0.98	1.25×10^{-5}
10	4.5	1200	1200	0.125	0.98	7.3×10^{-6}
100	4.5	8400	1200	0.125	0.98	1.04×10^{-6}

Col. c from Figure 2.

Col. d from Figure 1.

Col.e 150 m over value in Col. d.

Col f Value in Table 3 corresponding to H/σ_z in Col. e.

Col g Solutions to equation 3.

TABLE 5

y (m)	y/σ_y	$\exp - \frac{1}{2}(y/\sigma_y)^2$	C(y) gms/m^3
± 100	0.834	0.7	2.03×10^{-4}
± 200	1.67	0.25	7.25×10^{-5}
± 300	2.5	4.2×10^{-2}	1.22×10^{-5}
± 400	3.33	3.7×10^{-3}	1.07×10^{-6}

This is graphed in Figure 10

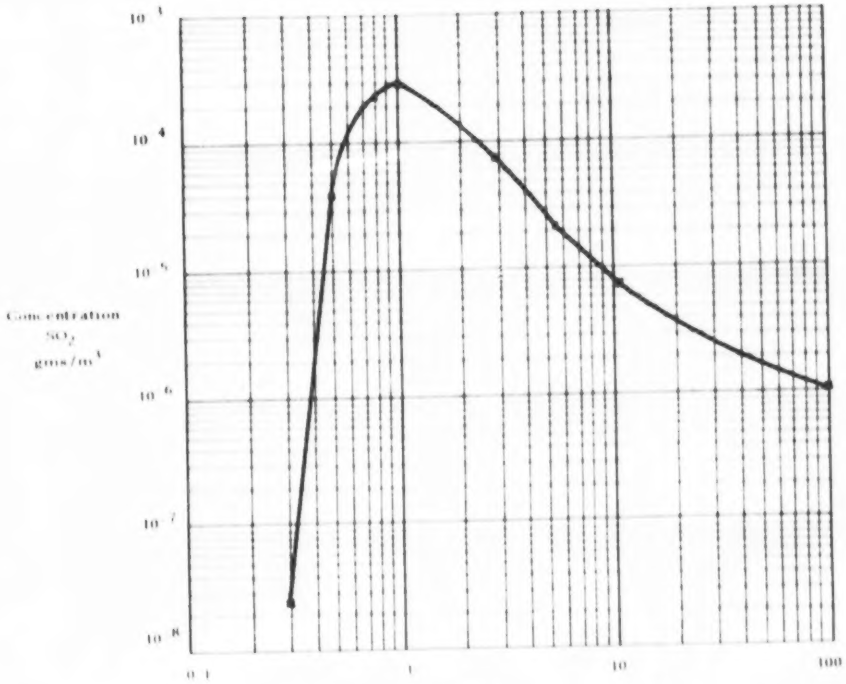


Figure 9. Concentration of SO_2(gms/m^3) as a Function of Distance (km). (Problem 2)

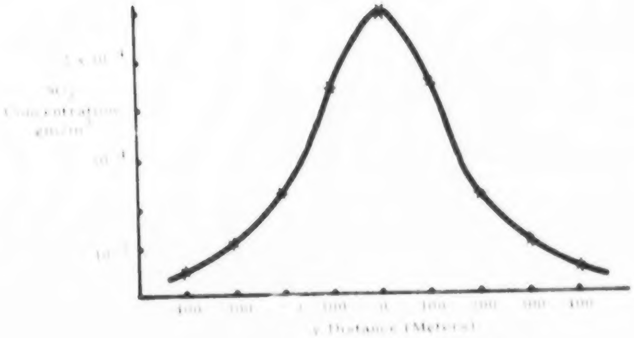


Figure 10. Concentration of SO_2 (gms/m^3) Across Wind at a Distance of 800 Meters (Problem 3)

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Answers to Exercise (Page 3-22)

1.	D	8.	2
2.	D	9.	8,5
3.	B-C	10.	0,198
4.	D-E	11.	3,5
5.	28,15	12.	1.4×10^{-6} sec/m^3
6.	55m	13.	10^6m^2
7.	1450		

EFFECTIVE STACK HEIGHT

J.L. Dicke

In any consideration of concentrations downwind from a source, it is desirable to estimate the effective stack height, the height at which the plume becomes level. Rarely will this height correspond to the physical height of the stack.

A high velocity of emission of the effluents and a temperature higher than that of the atmosphere at the top of the stack will act to increase the effective stack height above the height of the actual stack. The effect of aerodynamic downwash, eddies caused by the flow around buildings or the stack, and also the evaporative cooling of moisture droplets in the effluent may cause lowering of the plume to the extent that it may be lower than the physical stack height.

EFFECT OF EXIT VELOCITY AND STACK GAS TEMPERATURE

A number of investigators have proposed formulas for the estimation of effective stack height under given conditions: Davidson (1949), Sutton (1950), Bosanquet et al. (1950), Holland (1953), Priestley (1956).

A recent comparison of actual plume heights and calculations using six of the available formulas was made by Moses and Strom (1961). The formulas used were Davidson-Bryant, Holland, Scorer, Sutton, Bosanquet-Carey-Halton, and Bosanquet (1957). They found that "There is no one formula which is outstanding in all respects." The formulas Davidson-Bryant, Holland, Bosanquet-Carey-Halton, and Bosanquet (1957) appear to give satisfactory results for many purposes. It must be pointed out that the experimental tests made by Moses and Strom used stack gas exit velocities less than 15 m/sec and that temperatures of the effluent were not more than 35°C higher than that of the ambient air. Moses and Strom expect to make field tests using higher temperatures and higher stack velocities.

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Stewart, Gale, and Crooks (1958) compared effective stack heights for the Harwell reactor emitting radioactive Argon with computations using the formula of Bosanquet et al. (1950). The temperature of the gases was 50°C above that of the ambient air and stack gas velocity was 10 m/sec. At low wind speeds, agreement between formula and plume height were quite good. At wind speeds greater than 6 m/sec and distances greater than 600 meters from the stack the formula underestimates effective stack height.

Two of the formulas for estimation of effective stack height are given below. Both the Davidson-Bryant formula and Holland's formula frequently underestimate the effective stack height. Therefore, a slight safety factor is frequently made by using these formulas.

The Davidson-Bryant formula is:

$$\Delta H = d\left(\frac{v_s}{u}\right)^{1.4}\left(1 + \frac{\Delta T}{T_s}\right) \qquad (1)$$

Where:

ΔH = the rise of the plume above the stack

d = the inside stack diameter

v_s = stack gas velocity

u = wind speed

ΔT = the stack gas temperature minus the ambient air temperature (°K)

T_s = the stack gas temperature (°K)

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Any consistent system of units for ΔH, d, v_s, and u may be used. It is recommended that v_s and u be in meters/sec and d in meters which will give ΔH in meters.

The Holland stack rise equation is:

$$\Delta H = \frac{v_s d}{u} \left(1.5 + 2.68 \times 10^{-3} \, p \, \frac{\Delta T}{T_s} \, d \right) \quad (2)$$

Where:

ΔH = the rise of the plume above the stack (meters)

v_s = stack gas velocity (m/sec)

d = the inside stack diameter (meters)

u = wind speed (m/sec)

p = atmospheric pressure (mb)

T_s = stack gas temperature (^oK)

ΔT = as in equation (1) and

2.68×10^{-3} is a constant having units of (m^{-1} mb^{-1}).

It is recommended that the result from the above equation be used for neutral conditions. For unstable conditions a value between 1.1 and 1.2 times that from the equation should be used for ΔH. For stable conditions a value between 0.8 and 0.9 times that from the equation should be used for ΔH.

Since the plume rise from a stack occurs through some finite distance downwind, these formulas should not be applied when considering effects near the stack. Note that these formulas do not consider the stability of the atmospheric but only the ambient air temperature. Actually, stability should have some effect upon the plume rise.

Lucas et al., 1963, have tested Priestley's theory on stack rise at two power stations. These investigators write the formula for stack rise as:

$$z_{max} = \alpha \frac{Q^{\frac{1}{4}}}{u} \quad (3)$$

Where:

z_{max} = effective rise above the top of the stack (feet)

α = a variable affected by lapse rate and topography (ft^2 $MW^{-1/4}$ sec^{-1})

Q = the rate of heat emission from the stack in megawatts (MW)

u = the wind speed (ft/sec)

They determined α to be 4900 and 6200 for the 2 power stations under neutral conditions. Clarke (1968) states that if the exit velocity at the stack gases exceeds 2000 fpm (23mph), no rain will enter the stack. As an example, he found from a ten year summary of U.S. Weather Bureau wind data for Chicago that 98% of the days had a maximum wind velocity $\leq$ 20 mph.

EFFECT OF EVAPORATIVE COOLING

In the washing of effluent gases to absorb certain gases before release to the atmosphere, the gases are cooled and become saturated with water vapor. Upon release from the absorption tower further cooling is likely due to contact with cold surfaces of ductwork or stack. This causes condensation of water droplets in the gas stream. Upon release from the stack, the water droplets evaporate withdrawing the latent heat of vaporization from the air and consequently cooling the plume, causing it to have negative buoyancy, thereby reducing the stack height. (Scorer 1959).

The practice of washing power plant flue gases to remove sulfur dioxide is practiced at Battersea and Bankside power stations in London, where frequent lowering of the plumes to ground level is observed.

EFFECT OF AERODYNAMIC DOWNWASH

The influence of the mechanical turbulence around a building or stack may significantly alter the effective stack height. This is especially true under high wind conditions when the beneficial effect of high stack gas velocity is at a minimum and the plume is emitted nearly horizontally. The region of disturbed flow surrounds a building generally to twice its height and 5 to 10 times its height downwind. Most of the knowledge about the turbulent wakes around stacks and buildings have been gained through wind tunnel studies. Sherlock and Stalker (1940), (1941), Rouse (1951), Sherlock (1951), Sherlock and Lesher (1954), (1955), Strom (1955-1956), Strom et al. (1957), and Halitsky (1961), (1962),(1963). By using models of building shapes and stacks the wind speeds required to cause downwash for various wind directions may be determined.

In the use of a wind tunnel the meteorological variables that may most easily be taken into account are the wind speed and the wind direction (by rotation of the model within the tunnel). The plant factors that may be taken into consideration are the size and shape of the plant building, the shape, height, and diameter of the stack, the amount of emission, the stack gas velocity, and perhaps the density of the emitted effluent. The study of the released plume from the model stack has been done by photography (Sherlock and Lesher, 1954), decrease in light beam intensity (Strom, 1955), and measurement of concentrations of a tracer gas (Strom et al., 1957, Halitsky, 1963).

By determining the critical wind speeds that will cause downwash from various directions for a given set of plant factors, the average number of hours of downwash annually can then be calculated by determining the frequency of wind speeds greater than the critical speeds for each direction (Sherlock and Lesher, 1954). It is assumed that climatological data, representative of the site considered, are available.

It is of interest to note that the maximum downwash about a rectangular structure occurs when the direction of the wind is at an angle of 45 degrees from the major axis of the structure and that minimum downwash occurs with wind flow parallel to the major axis of the structure (Sherlock and Lesher, 1954).

It has been shown by Halitsky (1961),(1963) that the effluent from flush openings on flat roofs frequently flows in a direction opposite to that of the free atmosphere wind due to counter-flow along the roof in the turbulent wake above the building. In addition to the effect of aerodynamic downwash upon the release of air pollutants from stacks and buildings, it is also necessary to consider aerodynamic downwash when exposing meteorological instruments near or upon buildings so that representative measurements are assured.

In cases where the pollution is emitted from a vent or opening on a building and is immediately influenced by the turbulent wake of the building, the pollution is quite rapidly distributed within this turbulent wake. An initial distribution may be assumed at the source with horizontal and vertical variances of δy^2 and δ^2 in the form of a binormal distribution of concentrations. These variances are related to the building width and height.

The resulting equation for concentrations from this source has $(\sigma_y^2 + \delta_y^2)^{1/2}$ in place of σ_y and $(\sigma_z^2 + \delta_z^2)^{1/2}$ in place of σ_z in the point source equations.

EFFECT OF VERY LARGE POWER PLANTS

A power generating plant in the range of 1000-5000 megawatt capacity emits heat to such an extent that its own circulation pattern will be set up in the air surrounding the plant. It is doubtful that extrapolation of dispersion estimates from existing smaller sources can be applied to these large plants. Fortunately, the effluent plume will rise far above the ground and surface concentrations of pollutants downwind will increase by only a rather small amount most of the time. Such large plants will usually be engineered to minimize the effects of the two preceding topics. The "2 1/2" rule will tend to eliminate downwash and the "4/3[illegible]" rule for stack gas velocity will tend to eliminate entrainment of the effluent into the wake of the stack. (Fowler, [illegible])

Three weather conditions, however, can still bring ground level fumigations: high winds, inversion breakup, and a limited mixing layer with light winds. The climatology of these conditions will determine the magnitude and frequency of the pollution problem. [illegible] has presented nomograms for estimating ground level SO_2 concentrations for these three situations together with effective stack height formulas. Briggs (1965) has also presented a plume rise model which has been compared with data from various TVA power plants. Pooler (1967) introduced a slight modification to one of Briggs's equations and suggests this latter equation be substituted for the Pooler (1965) inversion breakup fumigation equation. Thus the basic equation for this important weather condition is:

$$\Delta H = \left[2.31 \frac{v_s r^2 T_A}{u} \left(\frac{\Delta T}{T_s} \right) \bigg/ \frac{d\theta}{dz} \right]^{1/3} \qquad (4)$$

Where: u = wind speed (m/sec)

r = inside stack radium (m)

T_A = ambient air temperature (°K)

$\frac{d\theta}{dz}$ = potential temperature lapse rate

Other symbols are defined as in equation (2) above.

A correction term for the additive effect of multiple-stack sources is also presented in Pooler (1967).

EFFECTIVE STACK HEIGHT

Other industries are also utilizing tall stacks for pollutant dispersion and anticipate results similar to the low measured ground level concentrations found near tall British power plant stacks. A case in point is the 1250 foot stack constructed in 1971 at a cost of $5.5 million to serve the Inco Copper Cliff smelter in the Sudbury district of Ontario, Canada. This gigantic stack is 116 feet in diameter at the base, tapering to just under 52 feet in diameter at the top. The interior diameter is 45 feet.

STATE OF THE ART

Considerable research is being conducted to further quantify the dilution effects of tall stacks and to develop better models for predicting the dispersion of power plant effluent in complex terrain and meteorological regimes. An extensive series of field experiments is being conducted, called the Large Power Plant Effluent Study (LAPPES), near Indiana, Pennsylvania and a report has been published by Schiermeier and Niemayer (1968). Field measurements include determining plume geometry by laser-radar, in-plume and ground level SO_2 concentrations, vegetation damage and meteorological conditions during the experiments.

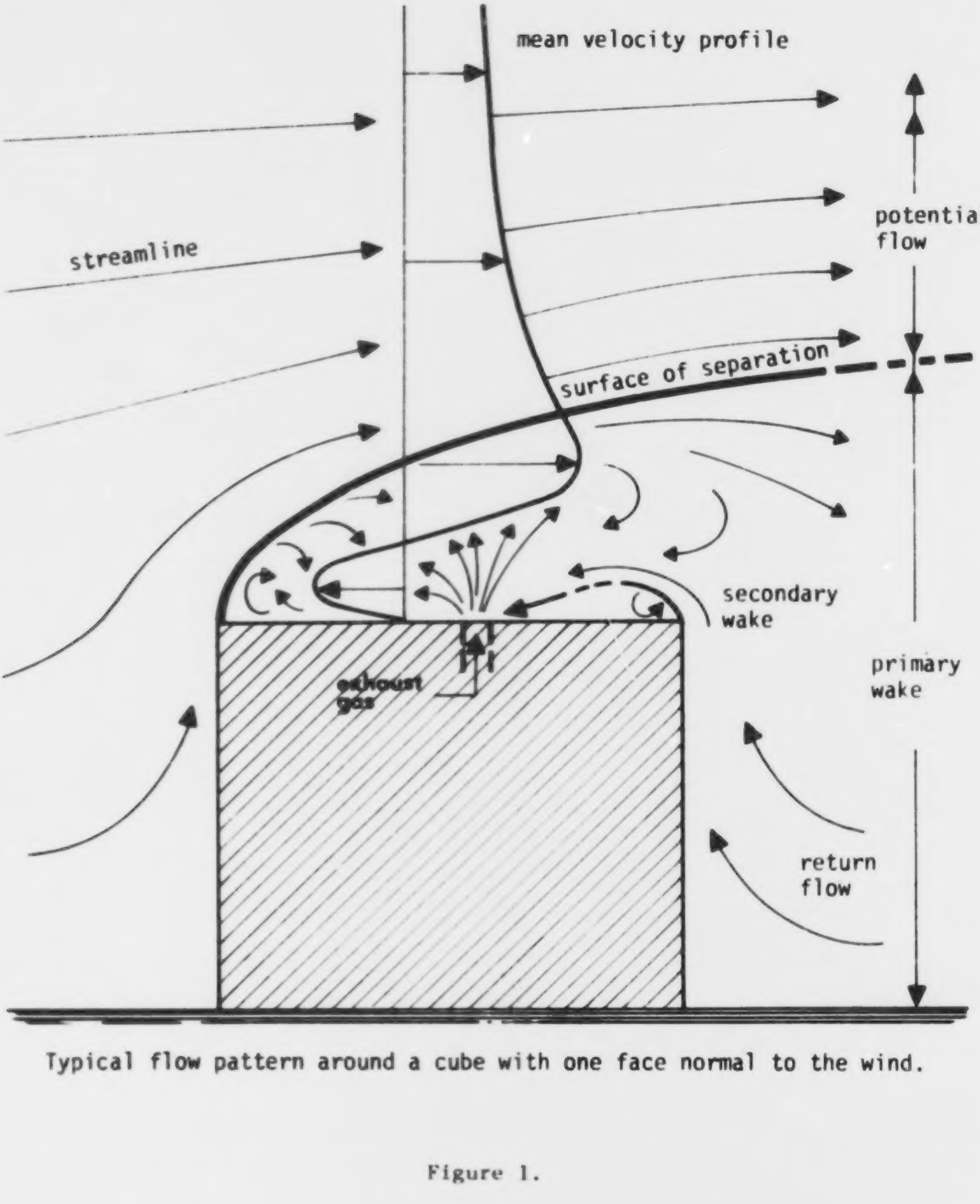
A summary of recent European studies dealing with plume rise and stack effluent dispersion is contained in the July 1967 issue of the journal Atmospheric Environment.

In addition another recent publication which contains a specific chapter on calculating effective stack height is the ASME Recommended Guide for the Prediction of the dispersion of Airborne Effluents (1968).

A comprehensive literature survey in this field was conducted by NAPCA and incorporated into an annotated bibliography of over 200 references. The publication, "Tall Stacks, Various Atmospheric Phenomena and Related Aspects" (1969), includes articles published through mid-1968.

A very recent series of EPA publications deal with air pollution aspects of emission sources. Of particular interest is OAP Pub. No. AP-96, "Electric Power Production - A Bibliography with Abstracts". Section D on air quality measurements and Section E on atmospheric interactions contain many specific references to plume rise determination, plume behavior, and pollutant concentrations associated with this class of sources.

Briggs in his recent publication, Plume Rise (1969), has presented both a critical review of the subject and a series of equations applicable to a wide range of atmospheric and emission conditions. These equations are being employed by an increasing number of meteorologists and are used almost exclusively within EPA. An important result of this study is that the rise of buoyant plumes from fossil-fuel plants with a heat emission of 20 megawatts (MW) - 4.7 x 10^6 cal/sec - or


mean velocity profile
streamline
potential flow
surface of separation
secondary wake
primary wake
exhaust gas
return flow

Typical flow pattern around a cube with one face normal to the wind.

Figure 1.

more can be calculated from the following equations under neutral and unstable conditions.

$$\Delta H = 1.6\, F^{1/3}\, u^{-1}\, x^{2/3} \qquad (5)$$

$$\Delta H = 1.6\, F^{1/3}\, u^{-1}\, (10h_s)^{2/3} \qquad (6)$$

where:

ΔH = plume rise
F = buoyancy flux
u = average wind at stack level
x = horizonal distance downwind of the stack
h_s = physical stack height

Equation (5) should be applied out to a distance of 10 h_s from the stack; equation (6) at further distances.

The buoyancy flux term, F, may be calculated from:

$$F = \frac{g\, Q_H}{\pi\, c_p\, \rho T} \sim 3.7 \times 10^{-5}\ \frac{m^4/sec^3}{cal/sec}\ Q_H \qquad (7)$$

where:

g = gravitational acceleration
Q_h = heat emission from the stack, cal/sec
c_p = specific heat of air at constant pressure
ρ = average density of ambient air
T = average temperature of ambient air

Alternatively, if the stack gases have nearly the same specific heat and molecular weight as air, the buoyancy flux may be determined from:

$$F = \frac{\Delta T}{T_s}\, g\, v_s\, r^2 \qquad (8)$$

where the notation has been previously defined.

In stable stratification with wind equation (5) holds approximately to a distance $x = 2.4\, u\, s^{1/2}$ where:

$$s = \frac{g}{T}\,\frac{\partial \theta}{\partial z}\text{ , a stability parameter} \qquad (9)$$

$\frac{\partial \theta}{\partial z}$ = lapse rate of potential temperature

Beyond this point the plume levels off at about

$$\Delta H = 2.9\left(\frac{F}{u\, s}\right)^{1/3} \qquad (10)$$

However, if the wind is so light that the plume rises vertically, the final rise can be calculated from:

$$H = 5.0\, F^{1/4}\, s^{-3/8} \qquad (11)$$

For other buoyant sources, emitting less than 20 MW of heat, a conservative estimate will be given by equation (5) up to a distance of:

$$X = 3x^{*} \qquad (12)$$

where:

$$x^{*} = 0.52 \left[\frac{sec^{6/5}}{ft.^{6/5}}\right] F^{2/5}\, h_s^{3/5} = \qquad (13)$$

distance at which atmospheric turbulence begins to dominate entrainment.

Anyone who is responsible for making plume rise estimates should familiarize himself thoroughly with Briggs' work.

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SECTION FOUR

AIR POLLUTION CLIMATOLOGY

AIR POLLUTION CLIMATOLOGY

J.L. Dicke*

INTRODUCTION

It is obvious that meteorology is very important in the transport and dispersion stages of the air pollution cycle. Meteorological factors are also related to the emission and reception stages. Since no region of the country is immune to air pollution problems, especially considering the increasing population and industrial areas, meteorologists have turned to broad scale or synoptic climatology to discover similarities and differences which may mean two locations hundreds or thousands of miles apart may have pollution problems arising from the same climatological influences.

In past years considerable research and climatological study were done on low pressure or cyclonic circulations. The severe weather changes, storms, aviation problems were associated with low atmospheric pressure systems and high pressure or anticyclones were greeted as breathers between storms, good flying weather, or at worst a hot spell. The harmful effects of stagnating air masses, very low wind speeds, clear skies and subsidence have been brought to the fore in recent years, unfortunately due to the sickness, death, property damage caused by high air pollution episodes.

Two factors which tend to increase air pollution concentrations are: light winds and stability of the atmosphere. Light winds cause only slight dilution of pollutants due to wind speed. Stability of the atmosphere limits the vertical dispersion of pollutants. High pressure systems or anticyclones are characterized by both of the above features: light winds and atmospheric stability.

SUBTROPICAL ANTICYCLONES

There are several areas of high pressure over the oceans that are quite permanent features of the general circulation. The Pacific anticyclone centered in the region between Hawaii and the west coast of North America, and the Azores anticyclone centered over the Azores in the Atlantic, both affect areas in the U.S. In the western portions of these highs, convergence and ascending motions are more prevalent than in the eastern portions where subsidence produces strong inversions. Although the Azores anticyclone extends westward occasionally enough to affect the Southeastern portion of the U.S., the influence of the Pacific anticyclone on the west coast is more important since the eastern portion of the anticyclone is affecting the region and the center of the high is nearer the affected area. This combined with the topography of the Los Angeles basin contribute greatly to the extent of the air pollution problem in that area.

TRACKS OF CYCLONIC AND ANTICYCLONIC SYSTEMS

Storm tracks have been compiled for many years, particularly hurricanes and tropical storms. The first general climatology of both cyclones and anticyclones was published by Klein in 1957 for the northern hemisphere. Visher in 1954 compiled the tracks of cyclones and anticyclones shown in Figures 1 and 2 where the width of the track indicates approximate frequency of occurrence.

Migrating anticyclones are generally of two types: those that originate in middle latitudes and move mainly eastward or those that originate at high latitudes and move southward.

The continuity of path and long life of these relatively stable systems are of particular importance because the pollutants emitted within a source region or along the track may easily have a trajectory similar to the track of the system and may finally be deposited great distances from their sources.

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Cyclones are generated in a much more diverse manner, particularly in different seasons. Low pressure areas tend to develop and track further north in summer, further south in winter. Source regions for cyclonic systems are quite numerous which means a high pressure area may be displaced from any one of the several directions indicated by the cyclonic tracks.

STAGNATING ANTICYCLONES

Climatological study has shown that the major air pollution episodes are usually related to the incidence of stagnating anticyclones,especially those lingering 4 days or more. During such periods surface wind speeds may be very low, subsidence inversions may severely limit vertical mixing in spite of warm daytime temperatures and the clear skies at night which often occur also restrict dispersion of pollutants through a small volume.

Korshover in 1957 studied the climatology of stagnating anticyclones east of the Rocky Mountains. By determining the number of stagnation cases (4 or more days) he prepared charts which delineate areas where stagnation occurred most frequently and found October in the southern Appalachians to have the highest frequency of occurrence with a secondary maximum in June. This is undoubtedly due in part to the extension of the Azores anticyclone into this region. Figure 3 illustrates the total number of stagnation days east of the Rockies during 1936-1956.

An experimental forecast program to recognize and forecast conditions of high air pollution potential was instituted in 1957. Results for certain periods have been reported (Niemeyer, 1960; Boettger, 1961; Miller and Niemeyer, 1963)

A comparable study by months is not available for the western United States; however, Holzworth in 1962 studied frequencies of the location of high pressure centers in the west. Figure 4 depicts the frequency of anticyclonic centers which occurred with a warm ridge aloft from 1949-1956. The majority of centers were in the Great Basin, bounded by 40-45N latitude and 110-120W longitude. The heavy lines on the figure are normal sea level isobars for November, December and January in millibars. The highest frequency of occurrence of quasi-stationary anticyclones coincides exactly. Holzworth also found that 90% of the days with quasi-stationary anticyclones occurred during October through February. This is in sharp contrast to the eastern United States where Korshover found only about 20% of the cases 4 or more days stagnation occurred from November through March.

INVERSION FREQUENCY

Atmospheric dilution of pollutants is a function of temperature gradient both in the vertical and horizontal as well as with time. Pollutants are dispersed very slowly when a stable stratified layer of air exists near the earth's surface. Hosler in 1961 presented a climatological study of the frequency of low-level stability which can be used to evaluate pollution potential for a given region. The tabulations he presented are for percent frequency of inversion and isothermal conditions at or below 500 feet above station elevation computed during a two-year period.

Two general areas of maximum inversion frequency predominate: one in the great basin areas of the western states, and one in the area of Eastern Tennessee, Northern Georgia, and the Carolinas.

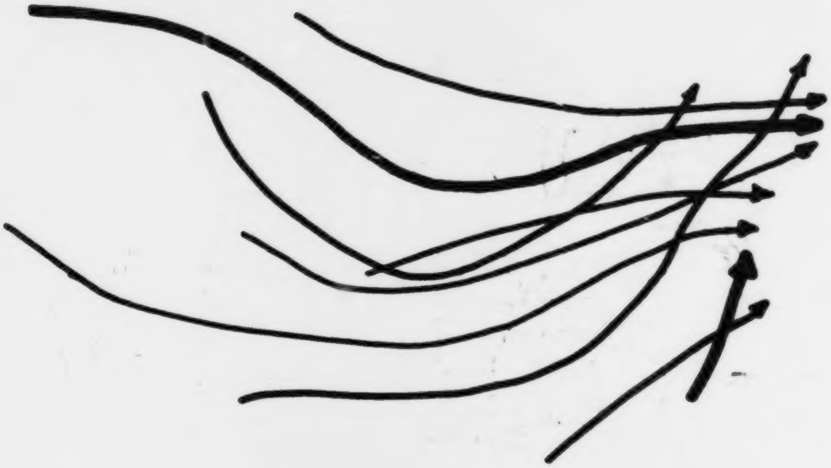


Figure 1. AVERAGE TRACKS OF CYCLONES

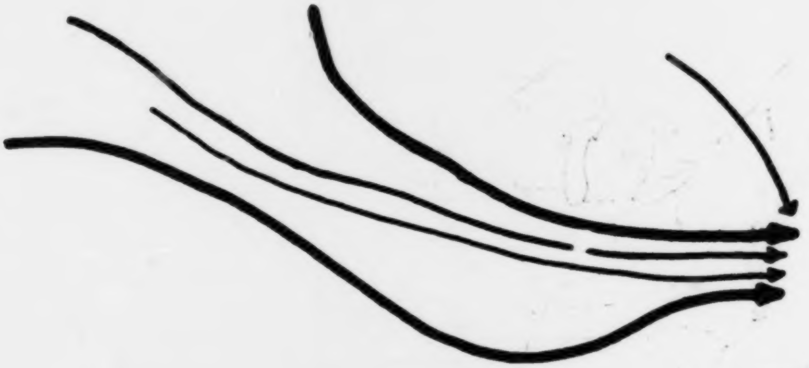


Figure 2. AVERAGE TRACKS OF ANTICYCLONES

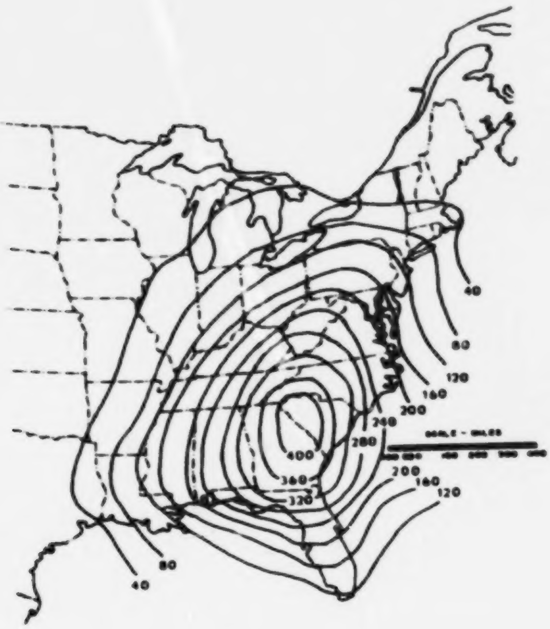


Figure 3. TOTAL STAGNATION DAYS (1936-1956)

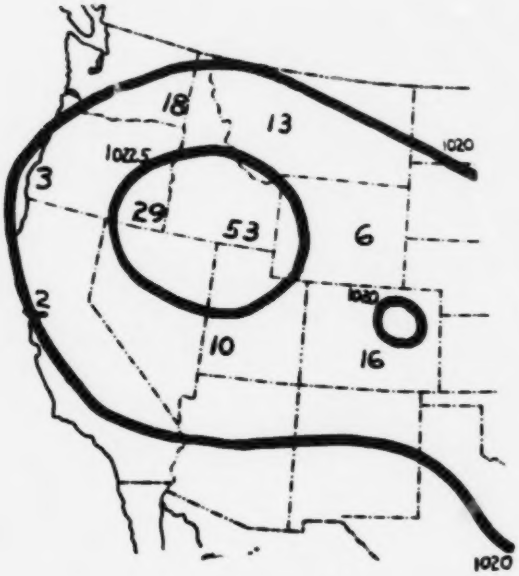


Figure 4. FREQUENCIES OF ANTICYCLONE CENTERS (1949-56)

Inversion frequency data must be tempered by regional and local considerations based on geography. Coastal stations reflect marine influences primarily resulting from advection whereas inland stations have inversions caused by radiation processes. Ocean temperature and land-sea temperature differentials are reflected in frequencies from most coastal locations. Inland stations are most often in valleys in the Rocky Mountain and Appalachian regions and consequently higher inversion frequencies would be expected. Urban-rural influences must also be considered when interpreting the data for a large city since most Weather Bureau radiosonde stations are located in semi-rural, suburban locations. With these climatic-geographic distinctions in mind, Hosler evaluated 8 general areas of the country and on an annual basis found the inversion frequencies listed in Table 1.

Also included in Table 1 is the annual average wind speed as compiled by Visher in 1954. For a more specific discussion of inversion frequencies by season for various areas refer to the original paper by Hosler.

MAXIMUM MIXING DEPTH

The concept and calculation of mixing depths was presented in Meteorologic Fundamentals. Continuing the discussion on temperature structure in the vertical, Holzworth in 1964 has prepared estimates of the mean maximum mixing depths for each month based on Weather Bureau radiosonde observations. Since Hosler has shown that marked stability at low levels is generally the rule at night outside of large urban complexes, it is important to know what mixing in the vertical can be expected in the daytime to alleviate possible air pollution episodes.

The major assumption of the mixing depth method is that vertical mixing is a function only of the vertical temperature structure at the time of the sounding and surface maximum temperature. Thus, it is evident that MMD's are not overall indices of potential pollution but must be used in conjunction with several other tools.

Table 1

Region	Annual average[*] wind speed (miles per hour)	Annual low-level[**] inversion frequency (percent of total hours)
Atlantic Coast	10-15	10-35
Appalachian Mountains	7-11	30-45
Great Lakes	9-15	20-30
Gulf Coast	9-12	10-35
Central Plains	8-15	25-40
Rocky Mountains	5-11	35-50
Northwest Pacific Coast	6- 9	25-30
West Coast	5- 9	35-40

[*] From Visher, (1954)
[**] From Hosler, (1961)

Mean MMD's are less than 1500 meters over the entire country during October through February except for southern Florida. Generally they are less than half this height in December and January. Along the middle Atlantic and New England coasts MMD's are quite shallow during the entire year. Relatively moderate wind speeds and frequent storms offset the effect of lower mixing depths.

During March through September, Holzworth found that MMD's were practically unlimited over the Rockies and Florida. Otherwise, most areas, MMD's are less than 1500 meters and, in late summer along the Pacific Coast, MMD's are less than 500 meters. Coastal regions in general, including the Great Lakes, show only small variations throughout the year.

WIND SPEED

Wind speed and mixing depth are the parameters commonly used in studying pollution potential as they determine the volume through which pollutants are mixed and diluted. Wind speed varies markedly throughout the country, throughout the day and throughout the area over a given location. Referring back to Table 1, the gross features are seen across the country by geographic regions. The West Coast generally has the lowest average annual wind speeds due to stratification of the air aloft from the semi-permanent anticyclone in the Pacific while increased storm passage and offshore wind flow have the opposite effect on the Atlantic Coast.

An extensive compilation of average daily wind speeds for the western United States was made by Holzworth in 1962. Using a definition of 5 mph or less daily average wind speed and no precipitation as being a light wind day, he typed 48 western cities according to the frequency of occurrence of these days. Most cities could be classified as: a) practically zero in all seasons (5); b) high in winter, low in summer (27); and, c) high in fall, low in summer (10) while only 6 had double classifications. The Pacific Northwest has the lowest frequency of light wind days in winter because storms most often enter the United States along the Washington-Oregon coast. Light wind days generally occur most often in winter and fall and least often in summer.

WIND DIRECTION PERSISTENCE

Calculations of short-term concentrations from a point source may be developed into an average dispersion climatology by expanding the evaluation in time through summation of successive periods. This will take into account the variability of wind direction, wind speed and dispersion conditions. In atmospheric diffusion modeling for time periods at least as long as a season, the equations are often integrated over an appropriate crosswind sector and summed. The persistence of the wind direction within various sectors gives guidance for appropriate time and space integration intervals.

Techniques for calculating the steadiness of the wind for various time periods have been presented by Singer (1967). The results of such a climatology, together with a probability statement, can be used to determine which areas will be highly affected and what the expected dosage will be for various time periods during which an air pollutant is released. In addition those meteorological conditions associated with a high steadiness value can be compiled and used in air pollution episode planning.

Van der Hoven (1969) has also investigated wind persistence probability using wind direction alone. The study was based on 5 years of data for 61 U.S. Weather Bureau stations throughout the United States. He found a correlation of about 0.9 between wind direction frequency and wind direction persistence. Wind roses that favor a particular sector also tend to persist in that sector. As a general rule the higher the wind speed the more persistent the wind direction will remain. Finally, the probability that the wind will remain within a 22 1/2 degree sector for 24 hours or more was less than 1% for all stations in this study.

FRONTAL TRAPPING

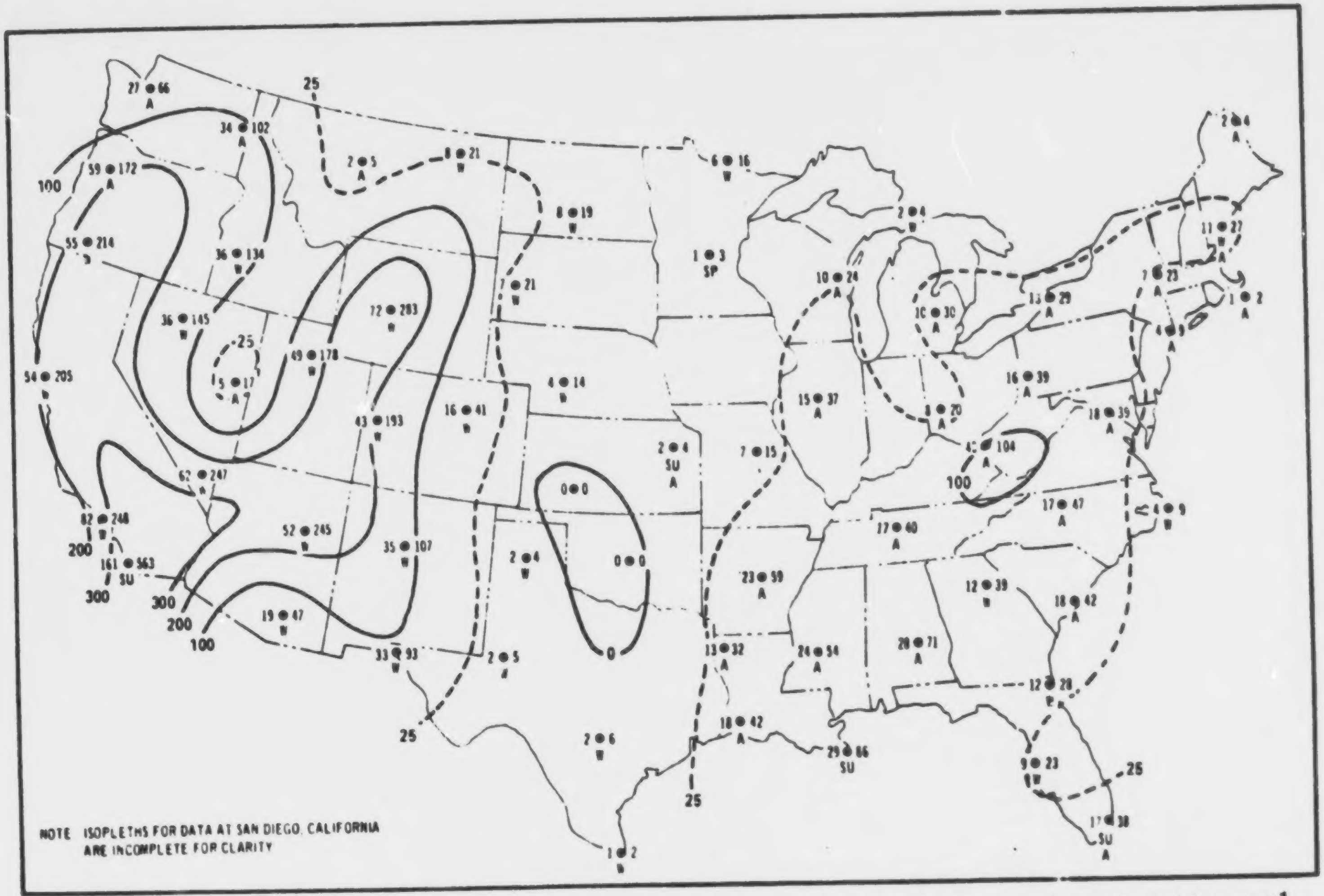
Since frontal systems are accompanied by inversions, trapping of air pollution beneath these inversions can occur. These may allow relatively high concentrations. Frontal trapping may occur with either warm fronts or cold fronts. Since warm fronts are usually slower moving and also the frontal surface slopes more gradually than that of a cold front, trapping will generally be more important with warm fronts. The surface winds ahead of an advancing warm front, i.e., in the region of the retreating cold air mass, will usually be much lighter than the surface wind behind an advancing cold front, at least in the sectors affected by trapping. Because of the orientation of frontal systems with respect to low pressure systems in the Northern hemisphere most surface winds associated with cold fronts are from the quadrant west through north and winds associated with warm fronts are from the east through north from a given source and cold frontal trapping to the east through south of the source.

AIR POLLUTION POTENTIAL CLIMATOLOGY

Miller (8) has published a method of forecasting afternoon mixing depths and transport wind speeds through the mixing depth based on data from 67 rawinsonde stations in the contiguous U.S. This method is utilized primarily in the National Air Pollution Potential Forecast Program.

Holzworth (3) has presented results of an air pollution climatology study which combine estimates of morning and afternoon mixing depths with average wind speeds through the mixing layer into an urban diffusion model for forecasting relative pollutant concentrations. The estimates of mixing depths and wind speeds were made for seven locations typical of several climatic regions in the United States. Diffusion model calculations were presented for four cities - New York, St. Louis, Salt Lake City, and Los Angeles - in the form of annual cumulative frequency curves which are a function of the size of the city. Highest relative concentration in the morning occurred at Los Angeles, followed by Salt Lake City, St. Louis, and New York. Afternoon relative concentrations followed the same order. However, calculations based on the assumption that all four cities were the same size as Los Angeles show that the highest relative concentration at the 50 percentile frequency in the morning would occur at Salt Lake City, followed by Los Angeles, St. Louis and New York. In the afternoon, the order is Los Angeles, Salt Lake City, St. Louis and New York with only slight differences between cities.

This study has now been expanded to other cities to provide an air pollution climatology for the contiguous United States, (Holzworth, 1971). Mixing height and wind speed data from 62 stations were calculated and tabulated by the National Climatic Center (NCC) based primarily on the five year period 1960 through 1964. Using a simple mathematical model of urban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12 ● 39
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18 ● 42
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200
19 ● 47
W
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28 ● 71
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13 ● 32
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24 ● 54
A
33 ● 93
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2 ● 5
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12 ● 28
W
18 ● 42
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25
2 ● 6
W
29 ● 66
SU
9 ● 23
W
25
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17 ● 38
SU
A
1 ● 2
W

NOTE ISOPLETHS FOR DATA AT SAN DIEGO, CALIFORNIA ARE INCOMPLETE FOR CLARITY

Figure 5. Isopleths of total number of episode-days in 5 years with mixing heights ≤ 1500 m, wind speeds ≤ 4.0 m sec^{-1}, and no significant precipitation (see text) - - for episodes lasting at least 2 days. Numerals on left and right give total number of episodes and episode-days, respectively. Season with greatest number of episode-days indicated as W (winter), SP (spring), SU (summer), or A (autumn).

diffusion, normalized pollutant concentrations averaged over a city as a function of mixing height, wind speed and city size were calculated. Frequencies of normalized pollutant concentrations for different city sizes were also prepared. Finally, episode-day maps of high meteorological potential are presented based on specified combinations of mixing height and wind speed. The criteria of mixing height $H \leq 1500$m and wind speed $U \leq 4$ m sec^{-1} are particularly important since they have been incorporated in the National Air Pollution potential forecasting program. Figure 5 illustrates that the meteorological potential for episodes is much greater in the West than in the East with barely 100 episode days at one eastern station and over 100 episode days at most western stations.

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SECTION FIVE

INTERRELATIONSHIPS-METEOROLOGY AND AIR POLLUTION

Urban Effect Upon Meteorologic Parameters
Atmospheric Turbidity
Atmospheric Chemistry of Air Pollution
Natural Removal Processes in the Atmosphere
Analysis of Air Quality Cycles

URBAN EFFECT UPON METEOROLOGIC PARAMETERS

There is hardly any meteorologic element that can be named that is not influenced to some extent by cities. It is, however, difficult to separate urban effects from microclimatologic effects since very few measurements have been made with the specific aim of comparing urban and non-urban measurements. There are several causes for the differences between urban and open country climates. One of these is the alteration of the surface, the change from meadow, forest or swamp to buildings and streets of concrete, brick, steel, and asphalt. Not only does this cause changes in reception and reflection of solar radiation, and evaporation but changes the roughness of the surface over which the wind moves. Another is the production of a sizable quantity of heat due to combustion processes carried on in the city. Another cause is the addition of material to the atmosphere in the form of dusts, gases, and vapors such as to change the atmosphere's composition in the vicinity of cities.

TEMPERATURE

The comparison of temperatures within cities with those outside reveal that city temperatures, especially at time of minimum, are higher (Mitchell, 1961). Also during the period right after sunset the city temperature does not cool as rapidly as does the country air due to heat content of buildings and radiation toward each other rather than toward the sky. Between sunrise and noon urban and non-urban temperatures are nearly the same. (Landsberg, 1956). The influence of the city extends in the vertical on the order of three times the height of the buildings (Duckworth and Sandberg, 1954). The average heat island effect over New York City extends to 300 meters and has been observed as high as 500 meters (Bernstein, 1968) Also, the change of temperature with height is quite different over the city especially at night. In the open country radiation inversions form frequently whereas in the city weak lapse conditions frequently exist through the night with a radiation inversion layer above the lapse conditions, (DeMarrais, 1961).

Since temperatures in the city are warmer than those of the surrounding countryside, the city's heating requirements are less by as much as 10%.

Variations between city and country temperatures are extremely noticeable at northern latitudes when the countryside is covered with snow but has melted in the city.

HUMIDITY

There are lower relative humidities in cities partly due to higher temperatures but there is also lower absolute humidity. Although little is available in the way of measurements, it is felt that lower absolute humidities are due to the rapid runoff of precipitation in the cities. Also the existance of little vegetation in the city reduces moisture received from evapotranspiration processes. (Landsberg, 1956).

PRECIPITATION

Precipitation is one of the most widely variable meteorological elements and because of this it is difficult to establish significant differences between urban and non-urban areas. However, numerous studies have been made which show either greater precipitation amounts and/or greater frequency of precipitation within cities. Schmauss, in 1927 showed 11 per cent increase of days with small amounts of precipitation occurring in Munich compared to stations outside the city. Bolgolepow, in 1928, reported an increase of 10 per cent in total amount in Moscow compared to a country station for 17 years of record. Ashworth noted in 1929 the increase of average annual precipitation over 3 decades amounting to 13 per cent. He also noted less increase for Sundays than for weekdays. Wiegel, in 1938, using a 35 year record, noted a 5 per cent increase in precipitation, as well as a 12 to 18 per cent increase in the number of days with precipitation for the Ruhr area of Germany. These are all reported in Landsberg (1956). Landsberg also reports a study for Tulsa where topographical effects are at a minimum and the urban area is confined to a rather definite area. In addition to an increase within the city over a 70 year period, there was an increase of 7 per cent in the city compared to surroundings for a 14 year period.

Two more recent studies by Changnon (1961 a, 1961 b) indicate there may be some urban effect upon precipitation over Chicago and the moderate-sized communities of Champaign, Urbana, Illinois.

The principal suspected causes of the increase of precipitation over cities is the increase of condensation nuclei over cities due to air pollutants and the increased turbulence over the city due to both increased roughness of the surface and release of heat from the city. Although water vapor is added to the air from combustion sources this is not expected to add significant precipitable water to have a major effect.

SNOW

Precipitation in the form of snow indicates to some extent the influence of temperature in the urban area. Kossner in 1917 and Maurain in 1947 indicated greater frequencies of snowfall outside as compared to within Berlin and Paris respectively. On the other hand, Kratzer in Munich in 1937 reported occurrances of snow within the city when none occurred in the surroundings, and Kienle in Mannheim, a heavy industry location, reported that snow fell from a fog and stratus layer on two successive days in January 1949 while none fell outside the urban area. It is probable that this was due to air pollutants furnishing condensation nuclei for supercooled water vapor. Landsberg (1968) estimates a 5% average decrease in snowfall for urban areas.

CLOUDINESS

From climatological records there seems to have been a slight increase in cloudiness over the years but this has been so slight (less than 1/10 of mean sky cover) that for so subjective a measure as sky cover this may not be significant. Any increase may be primarily due to city fogs, as increases in early morning cloud cover seems to be greatest. Nearly all large cities show a decrease in the number of clear days over that observed in adjacent rural areas. The primary effects may be expected to be due to addition of condensation nuclei by air pollution and the release of additional water vapor. Kratzer in Munich indicated in 1937 an 8 per cent increase in summer cloudiness compared to a 3 per cent increase in winter cloudiness over the city (Landsberg, 1956). This may indicate that surface roughness increasing turbulence may play a part in the formation of cumulus type summer clouds.

WIND

Because of the increase generally of the size of the roughness elements in the city over that in the rural areas, wind speeds are decreased within the city. Also the frequency of calms is increased on the order of 5 to 20 per cent (Landsberg, 1956). Recently Pooler (1961) has shown that under conditions of light stable flow that an inflow of air toward the center of the city of Louisville occurs (heat island effect). In addition to the decrease of wind speed in cities, there is of course channeling of the wind in the canyons formed by alternating streets and groups of buildings.

RADIATION

The decrease of solar radiation within cities as compared to rural areas is on the order of 15 to 20 per cent. This is due to the absorption, reflection, and scattering of particles in the atmosphere, and the absorption of gases. These particles and gases are primarily the result of air pollution. The radiation most affected is that of the ultraviolet with the infra-red least affected. This is of importance due to the bactericidal effect of ultraviolet radiation.

Recently, McCormick (1960) has begun measurements of the attenuation of the solar beam at 0.5 micron wave length in order to have an objective measure of the entire pollution layer. In terms of duration of sunshine, Landsberg (1968), presents a range of 5-15% as the decrease of this parameter in urban areas. Randerson (1970) has showed an average of 23% loss in intensity of light attributed to pollution in Houston, Texas.

VISUAL RANGE

The decrease of visibility in urban areas is probably the most noticeable of meteorological differences between urban and rural areas. The increase of fogs in cities has already been mentioned under cloudiness. Comparisons between hourly observations of visibility at city locations and at rural locations (Landsberg, 1956) have shown higher frequencies of fog, smoke, and low visibilities than in neighboring rural areas.

Holzworth and Maga (1960) analyzed visibility measurements from California locations to determine if trends were noticeable which might be caused by increases in air pollution. Results indicated that several cities showed trends toward lowering visibilities. Another showed lowering visibilities until efforts at controlling certain pollutants were made after which no trend was discernible.

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ATMOSPHERIC TURBIDITY

J.L. Dicke

INTRODUCTION:

Fine particulates, dust, and various aerosols produce haze, reduce visibility. The reduced visibility may be used, in a qualitative sense, to judge the degree of particulate air pollution present over a given location. Often, this is the only way by which the average person recognizes and is aware of the presence of air pollution. Particulates have specific optical properties which can be used to determine their spatial and temporal variation, particularly over urban areas. The presence of particulates characterized almost exclusively a property of the atmosphere termed "turbidity", especially at the wavelength of 0.5 micron. Turbidity generally means the degree of transparency of a cloud-free atmosphere to visible radiation. The vertical distribution of aerosol materials up to 2000 ft. is the basis for considerable research effort and preliminary results in this country have been published by McCormick and Baulch (1962).

THEORY:

The transmission of solar radiation through the atmosphere depends primarily on Rayleigh scattering (molecules), scattering and absorption by dusts and aerosols, and selective absorption by gases. At a given wavelength, λ, the transmission through the atmosphere can be written, following McCormick and Baulch above:

$$I(\lambda) = I_o(\lambda)\, e^{-\sigma M}$$

where

$I(\lambda)$ = intensity of incident radiation
(λ) = extraterrestrial radiation value
M = optical path length of air mass
σ = attenuation coefficient
$\frac{I(\lambda)}{I_o(\lambda)}$ = transmissivity

At 0.5 micron the attenuation is due almost entirely to Rayleigh scattering and the scattering and absorption by dusts and aerosols. Volz's work (1959) led McCormick and Baulch to develop a working equation.

$$I = \frac{I_o}{F}\, 10^{-(aK \frac{P}{Po} + B) M}$$

where

F = reduction factor for mean solar distance
a = atmospheric extinction coefficient of pure air including ozone
K = factor to allow for differences between optical path length of the atmosphere for air, haze and ozone.
P,Po = ambient and sea level pressure
B = extinction coefficient for dust, haze, etc. The turbidity.
M = relative optical path length or air mass

Thus, by observing I, B values can be determined from a nomogram since all the terms can be obtained independently or approximated.

B is directly related to the amount of the atmospheric particulate and can serve at least as an index of pollution, even if it is not exactly quantitative. Values of B are obtained under clear skies, or at least with no clouds between the observer and the sun, in a relatively easy manner. The data can be used to evaluate aerosol and dust loadings over the observation point.

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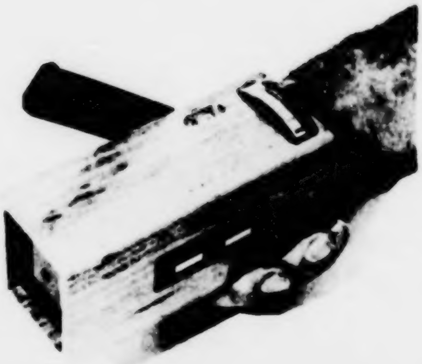

Figure 1. SUN PHOTOMETER

MEASUREMENT:

The instrument used, Figure 1, is called a sun photometer and is modeled fairly closely to that first developed by Volz. The small wooden box contains a filter, photoelectric cell, microammeter and level. The movable diopter mounted on a pivot is used to determine optical path length (relative air mass M). The Kodak Wratten 65 filter-photocell combination results in an instrument sensitive to essentially monochromatic light at $\lambda = 0.5$ micron. The observations must be made where there are no obstructions between the instrument and the sun although very thin cirrus clouds are allowable. The optical air mass M must be determined for every incident radiation observation. Then, using a nomogram, B can be read directly. Values of B generally range from 0.02 in very clean air to more than 0.60 in dirty air.

RESULTS:

In Cincinnati, Ohio, a large number of vertical observations of turbidity have been made, both from a helicopter and from roofs of tall buildings. At the same time vertical temperature soundings were made and the transmissivity compared to the lapse rate. The effects of temperature stratification can easily be demonstrated. McCormick and Baulch have shown that very often more than one-half of the solar radiation incident at 2000 ft. (height of helicopter sounding) is attenuated by the 1000 ft. closest to the ground during times of high air pollution. From surface observations of B, i.e., B_o, an idea of the particulate loading may be approximated by the relation:

$$m \approx 10^3 B_o$$

where

m = mass loading in micrograms per cubic meter

B_o = turbidity at ground level

It must be kept in mind, however, that the photometer "sees" only the aerosols in the 0.1 - 1.0 micron radius size range. Under high relative humidity conditions, the $10^3 B_o$ factor will result in calculated mass loadings that are too high when compared to actual Hi-vol samples. Erroneous estimates of mass loading at ground level will also occur if there is a significant haze layer aloft.

An early summary of the atmospheric turbidity program in the San Francisco Bay Area has been presented by Bell (1963). Results of research experiments on the vertical diffusion of aerosols over a city have been published by McCormick and Kurfis (1966). Two recent papers which deal with the effects on climate of observed increasing turbidity values with time have been written by McCormick (1967) and McCormick and Ludwig (1967).

NETWORK:

Turbidity observations are being made at about 44 locations around the country at universities, research facilities, Weather Bureau Stations, etc., as part of an experimental program (see Figure 2). Each month observational forms from each station are mailed to the Division of Meteorology in Raleigh, North Carolina. The main objective of this program is to obtain a climatology of background readings of the principal air masses and synoptic situations affecting each location. An example is shown in Figure 3 for continental polar air mass in the fall. Each quarter a summary listing of all observations is prepared and a copy sent to each contributor. After sufficient information is assembled and "normal" monthly frequency distributions are established, a relatively quick appraisal of the air pollution envelope over a given area may be possible.

Analyses of 5 years of turbidity measurements made with Volz sunphotometers at a network of stations in the United States by Flowers, et al, (1969), have produced the following conclusions:

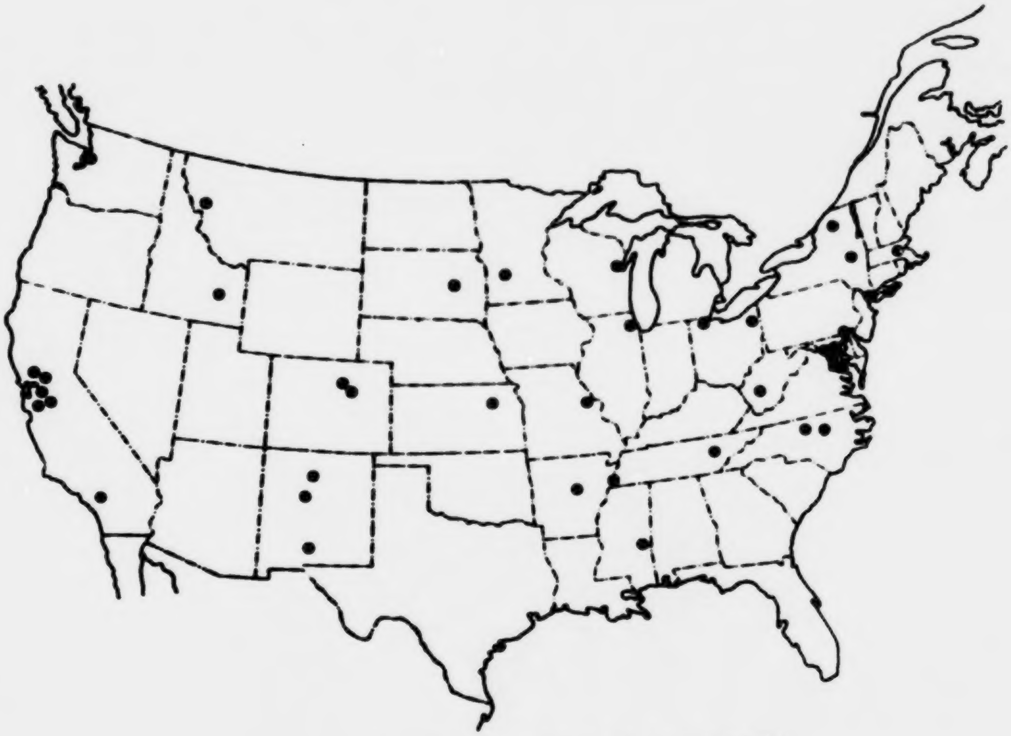

Figure 2 Turbidity Network (January 1970)

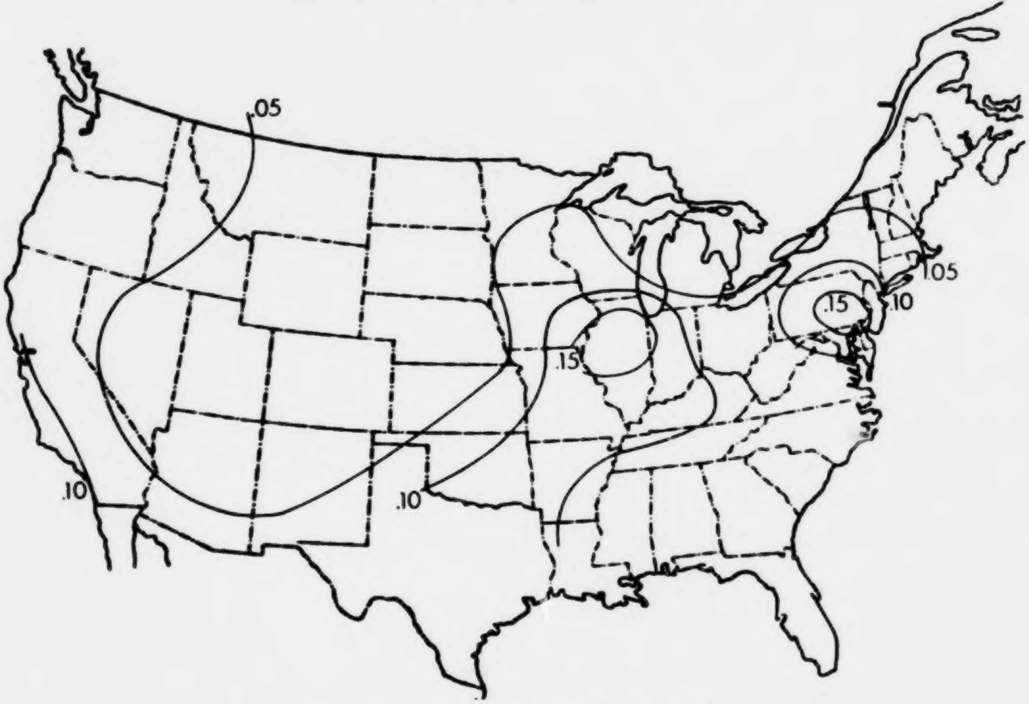
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Figure 3 Turbidity, Continental Polar – Winter

1) On an annual basis, lowest turbidity is observed over the Rocky Mountain area, and highest in the eastern United States.

2) Mean monthly turbidity values for all stations indicate higher turbidity in summer than in winter.

3) The minimum turbidity observed at sea level is near 0.020.

4) On the average, lowest turbidities are observed in polar continental air masses in winter and highest in maritime tropical air masses in summer.

5) Turbidity values are usually lower immediately after the passage of a cold front.

6) Precipitation in itself does not appear to have a noticeable effect in lowering turbidity.

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ATMOSPHERIC CHEMISTRY OF AIR POLLUTION

J. L. Dicke[*]

The solution of many air pollution problems involves utilizing knowledge of the chemistry of the atmosphere when it may be termed "clean" and when it is "dirty." Also, the nature of the air pollutants as they react as a whole must be determined. In general the two classes of polluted smogs are called either the London type - a reducing smog where contaminants form nuclei for condensation of water vapor into fogs -- or the Los Angeles type - an oxidizing smog where contaminants are photolysed to irritants.

I SOLAR RADIATION

The sun approaches a perfect blackbody radiator most closely in the region of 6000°K. Its maximum energy per wavelength occurs at 4500Å, while its maximum photon emission occurs at 6000Å. Photons produce many chemical and energy changes in matter at the molecular level upon absorption by upsetting vibrational, rotational and electronic balance. Vibrational and rotational changes occur mainly in the infrared region while electronic shifts need the higher energy of the ultraviolet range.

II PHOTOCHEMICAL REACTIONS

There are four main steps in a photochemical reaction which occur in time sequence: (1) Radiation, (2) Absorption, (3) Primary Reactions, and (4) Secondary reactions. We are mainly interested in substances which absorb photons in the 3000-7000 Å spectral region.

ABSORBERS	NON-ABSORBERS
O_2	N_2
O_3	H_2O
NO_2	CO
SO_2	CO_2
HNO_2 - HNO_3	NO
RCHO	SO_3 - H_2SO_4
RCO	RCH
RCOO	RCOH
Particulates	RCOOH

III OXYGEN

The most important photochemical reactions involve the very reactive single oxygen atom.

$$O + O_2 \longrightarrow O_3$$

$$O + \text{Olefins} \longrightarrow \text{Several Fragments}$$

$$O + NO_2 \longrightarrow NO + O_2$$

$$O + SO_2 \longrightarrow SO_3$$

These atoms are produced by two main reactions:

$$\left.\begin{aligned} NO_2 + h\nu &\rightarrow NO + O \\ O_3 + h\nu &\rightarrow O_2 + O \end{aligned}\right\} \text{Major fragments of photochemical reaction in the atmosphere.}$$

Oxygen atoms are produced at the rate of 150 pphm hr^{-1}, but because of their reactivity, their stationary concentration in air usually is only 1-2 ppht (parts per hundred trillion).

IV OZONE

Ozone is very important as a reactant in photochemical type smog. It is produced through the photolysis of nitrogen dioxide and the reactive oxygen atom.

$$NO_2 + h\nu \rightarrow NO + O$$

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$$O + O_2 \rightarrow O_3$$

Ozone is a strong oxidizer and its main atmospheric reactions are:

$$90\% \quad O_3 + NO \rightarrow NO_2 + O_2$$

$$\text{Equal Rate} \begin{cases} O_3 + NO_2 \rightarrow NO_3 + O_2 \\ O_3 + \text{Olefins} \rightarrow \text{Free radicals, other organic fragments} \end{cases}$$

V SULFUR DIOXIDE

Sulfur dioxide is the major sulfur containing compound formed during fuel combustion. Hydrogen sulfide is easily oxidized to sulfur dioxide in air especially in sunlight. In sunlight sulfur dioxide reacts with either atomic or molecular oxygen to form an aerosol particularly if water vapor is present. This aerosol is dilute sulfuric acid when uncontaminated with the particulates, etc., which are found in reducing type smogs. Sulfur Dioxide also reacts with organics to form various sulfonic acids which are also irritants. Relative humidity plays the most important role in photochemical reactions of sulfur dioxide by determining particulate-aerosol formation.

VI ORGANIC COMPOUND REACTIONS

The range of classes of organic compounds emitted from various processes and industries is very wide. Most of the higher molecular weight products settle rapidly, but short carbon chain molecules tend to be more reactive as ionic character outweighs the usual covalent nature of organic materials and they are very important as irritant progenitors. Absorption of photons often leads to dissociation into free radicals - short fragments with extra electrons which are extremely reactive. Olefins, aldehydes, ketones, peroxides, are classes which easily absorb photons and form free radicals and are among the usual products of combustion, especially from oil base fuels.

VII NITROGEN OXIDE REACTIONS

Oxides of nitrogen are formed in practically all combustion processes in air, but the diurnal peaks and valleys of concentration are a matter of concern in air pollution studies due to the high buildup in the morning hours within urban areas as vehicular traffic reaches a peak. The sequence of reactions

$$NO_2 + h\nu \rightarrow NO + O$$

$$O + O_2 \rightarrow O_3$$

$$NO + O_3 \rightarrow NO_2 + O_2$$

is the fastest, most important, and results in the highest concentrations of actual and potential irritant producing compounds in air pollution - atmospheric chemistry. Second in importance, photochemically, is olefin photolysis and ozone-organic molecule interaction. Other nitrogen oxide reactions of less importance are:

$$NO_2 + O_3 \rightarrow NO_3 + O_2$$

$$NO + NO_2 + H_2O \rightarrow 2\,HNO_2$$

$$N_2O_5 + H_2O \rightarrow 2\,HNO_3$$

VIII NON-PHOTOCHEMICAL REACTIONS

A secondary reaction following photochemical reaction which is very important is:

$$O_3 + \text{Olefins} \rightarrow \text{free radical fragments}$$

Olefins are the most important beginning class of organic compounds for production of irritants and phytotoxicants.

Reaction with water vapor:

$$NO_x + H_2O \rightarrow HNO_2 - HNO_3$$

$$SO_3 + H_2O \rightarrow H_2SO_4$$

Other inorganic and organic classes of compounds are also emitted to the atmosphere such as: fluorides which quickly react with various surfaces, ammonia which forms acids, hydrogen sulfide which reacts with organics and forms sulfates, carbon monoxide which slowly oxidizes to carbon dioxide and organic amines which oxidize to acids. The above reactions are generally not of importance except in small localized areas.

IX PARTICULATE MATERIAL REACTIONS

Particulate matter is of an entirely different size category than we have examined thus far. As such, it provides reactive surfaces and can act as a third body and catalyst. Interaction with a particulate surface can cause either an energy level change or a complete chemical change.

Examples of the former are:

$O_{\lambda_1}2 + M \rightarrow O_{\lambda_2}2 + M$ Change in absorption

$\cdot CH_3 + M \rightarrow CH_3 + M$ Termination of free radical

Examples of the latter are:

$$ZnO(M) + H_2O \text{ vapor} \xrightarrow{h\nu} H_2O_2 + M$$

Catalyzed by photons

$$SO_2 + H_2O \text{ drop} \rightarrow H_2SO_3 \text{ drop}$$

$$H_2SO_4 \cdot H_2O \text{ drop} + CaCO_3 \rightarrow CaSO_4 + CO_2 + H_2O$$ Change in particulate

X KINETICS IN ATMOSPHERIC CHEMISTRY

Without becoming involved in the rigors of kinetic theory, a few elementary definitions should be stated. The basis for determining the importance of any photochemical reaction, stationary concentration, rate of reaction, etc., is the Stark-Einstein Law which states that one photon must be absorbed to initiate photolysis. From this is defined the important equation:

$$k_a = \frac{I_a}{jc}$$

Where k_a is the specific absorption rate, I_a is the rate of absorption, j is a conversion factor, and c is the concentration of the absorbing substance. k_a represents the average fraction of absorbing molecules which receive photons per unit time. Primary quantum yield is very important as it tells us what percent of molecules that absorb photons will actually react to the absorbed energy via a specific process. Absorption of a photon may result either in energy level change, shown by fluorescence, or chemical change, shown by dissociation or direct reaction. The rate of formation of excited molecules A' is given by:

$$+ \frac{d(A')}{dt} = I_a = k_a (A) = k_a c \quad \text{where}$$

(A) = c the concentration of the absorber.

For secondary photochemical reactions rate constant is important. For a bimolecular reaction $A + B \rightarrow C + D$ the decrease in concentration of A will be:

$- \frac{d(A)}{dt} = k_1 (A)(B)$ where k_1 is the rate constant of the reaction. In general, the larger the rate constant, the more probable and more important part the reaction plays in the atmosphere.

XI SUMMARY

Thus, a knowledge of what general reactions take place in the atmosphere under different meteorological conditions can help answer questions concerning relative importance of contaminating substances. From a meteorological point of view, relative humidity and percent possible sunshine are the most important parameters to consider. This is because nitrogen dioxide-olefin photolysis and the reactions which follow are sunshine dependent and the sulfur dioxide-particulate reactions are largely humidity dependent. Next to consider is precipitation which functions as a removal method and low wind speed which causes the atmosphere to function as a stable reaction vessel. Extremes of temperature either help catalyze photochemical reactions, as in Los Angeles, or enhance fog formation - particulate - SO_2 reactions, as in London.

The state of knowledge of atmospheric chemical reactions and interactions leaves a good bit to be desired as the subject is very complex. Experiments in all the areas discussed are increasing our knowledge and the total picture is slowly emerging.

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NATURAL REMOVAL PROCESSES IN THE ATMOSPHERE

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I INTRODUCTION

All too often, atmospheric removal processes are considered to result in aggravating consequences such as depositions of fly ash, soiling of clothing and painted surfaces, and creating a general nuisance. However, these are the processes by which impurities are removed from the air such that the pollutant concentrations do not continually increase. Without such mechanisms, the atmosphere would ultimately become untenable.

The removal of material from the atmosphere may occur in a number of different ways. Particles large enough and heavy enough will settle to the ground due to the action of gravity. Some gaseous material may be removed by adsorption upon particulate matter in the atmosphere or by chemical reactions changing the material into a new compound. Adsorption may also take place at the ground by the earth's surface or by vegetation. Impaction of particles onto buildings and vegetation and turbulent impaction upon the earth's surface are very significant removal processes. Precipitation also removes material from the atmosphere by interception of particulates by falling raindrops (washout) or by raindrop formation within clouds and subsequent falling as precipitation (rainout).

A Gravitational Settling

A freely falling particle within the size range found in dusts, smokes, and mists rapidly attains a constant or terminal velocity when the aerodynamic drag on the particle is equal to the weight of the particle. When the particle is of a size comparable with the mean free path of the gas molecules, bombardment by the molecules results in a random or Brownian. motion which is superimposed on its downward motion. In considering falling speed, it is desirable to take the simplest case of a rigid spherical particle falling independently of other particles and not so large as to cause inertia effects from the displaced gas to arise, then Stokes' law applies. A spherical particle of density D falling through a medium of density ρ is accelerated under the action of gravity with a force:

$$f = \frac{4}{3} \pi (D - \rho) r^3 g \qquad (1)$$

Equation (1) represents the difference between the unimpeded fall of the particle ($\frac{4}{3} \pi D r^3 g$), and the buoyant force of the air ($\frac{4}{3} \pi \rho r^3 g$). r is the radius of the particle and g the acceleration of gravity. The accelerating force is opposed by a frictional force arising from the viscosity of the air and the turbulence induced in the air by the passage of the drop. A measure of the turbulence is given by a dimensionless parameter, the Reynold's number, that enters in the theory of the flow of fluids. The Reynold's number is defined as:

$$R_e = \frac{2 \rho r v}{\mu} \qquad (2)$$

where v is the relative velocity of the particle to the air of density ρ and viscosity μ. 2 r is the principal cross-sectional dimension of the particle. The ratio:

$$\eta = \frac{\mu}{\rho}$$

is called the kinematic viscosity and has dimensions of $cm^2 \ sec^{-1}$. The generalized resisting force on spheres has been found to be of the form:

$$f_r = 6 \pi \mu r v \left(\frac{C_D R_e}{24}\right) \qquad (3)$$

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C_D is called the drag coefficient and is the constant of proportionality between the measured force fr and the physical quantities in the equation. For low Reynold's numbers, $R_e < 1$, $C_D R_e / 24 = 1$, and equation 3 becomes:

$$f_r = 6\pi \mu r v \tag{4}$$

Equation 4 is called Stokes' Law.

C_D is not a constant but is a function of the Reynold's number. However, since C_D varies only slowly with r and v, it is useful to use equation 2 to write equation 3.

$$f_r = \frac{\pi}{2} C_D \rho r^2 v^2 \tag{5}$$

Thus, over a limited range of r and v, an average value of C_D may be selected.

Freely falling particles accelerated by a force given by equation 1 are opposed by a constantly resisting force given by equation 3. A point is reached where the two forces balance one another and equilibrium exists. At this point, the velocity reaches a maximum, called the terminal velocity. By equating equation 1 and 3, the terminal velocity v_T becomes:

$$v_T = \frac{2}{9} \frac{(D - \rho)}{\mu} g \left(\frac{24}{C_D R_e} \right) r^2 \tag{6}$$

For most of our applications, $D \gg \rho$ so that $D - \rho = D$ to all practical limits. When Stokes' Law is followed (valid for unit density particles in air for $r \leq 40$ microns) equation 6 becomes:

$$v_T = \frac{2}{9} \frac{Dg}{\mu} r^2 = \frac{1}{18} \frac{Dg}{\mu} a^2 \tag{7}$$

Calculation of v_T by equation 7 is straightforward. Once Stokes' Law has become invalid, the calculation of v_T from equation 6 becomes tedious because v_T is explicit in the definition of R_e and implicit in the definition of C_D. Table 1 gives values of a, R_e, and v_T for unit density spheres at sea level pressure.

Table 1. A Short Table of Terminal Velocities, Reynold's Number, and Correction Terms to Stokes' Law for Unit Density Spheres

Diameter (microns)	$\frac{C_D R_e}{24}$	v_T (cm/sec)	R_e
20	1.00	1.24	0.017
50	1.00	7.72	0.268
80	1.00	20.	1.11
200	1.68	72	9.61
400	2.98	162	43.2
800	5.94	327	175
1200	9.41	464	372
2000	18.7	649	866

Physical Meteorology - J.C. Johnson, Wiley and Sons 1954. Page 230.

Thus, particles large enough or dense enough to have appreciable terminal velocities will fall to the ground within rather short travel distances, depending on their height of release. This process constitutes a significant removal process for very large particles, of fly ash or dusts from cement plants. Because of the inertia of these particles, their reaction to the turbulence in the atmosphere is retarded. Also, because of their settling, they are in motion relative to specific eddies. Therefore, the action of settling actually changes the diffusion of these particles relative to what would occur with gases.

The concentrations in air of an effluent released from a single source can be expressed in the Gaussian form:

$$X = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp \left[-\frac{1}{2} \left(\frac{y^2}{\sigma_y^2} + \frac{H^2}{\sigma_z^2} \right) \right] \tag{8}$$

Where:

X represents the concentration in gm/m^3

Q represents the source strength in gm/sec

$\bar{u}$ represents the mean wind speed in m/sec

y represents the distance crosswind from the plume axis in meters

H represents the source height in meters

$\sigma_y^2 \ \sigma_z^2$ represents dispersion coefficients in m^2

This equation describes the distribution of concentration only when there are no processes depleting the cloud. One method used for correcting this equation for deposition amounts to permitting the diffusing plume to settle at the average terminal velocity of the particles as the material travels downwind (see p. 93, Meteorology and Atomic Energy). Thus, the height of emission is decreased with distance according to the settling velocity. The corrected emission height is then substituted into the diffusion equation. The corrected height of emission, H', is given by the following equation:

$$H' \text{ (meters)} = H \text{ (meters)} - \frac{v \text{ (m/sec) } x \text{ (m)}}{\bar{u} \text{ (m/sec)}} \tag{9}$$

Where H is the effective stack height of the source, v is the settling velocity determined by Stokes' Law, x is the distance downwind, and $\bar{u}$ is the mean wind speed. Van der Hoven (1962) used a deposition model of the tilted plume type to estimate the deposition from ground tested nuclear engines. As explained by Csanady (1957), the tilted plume model should have a further correction for the source strength term for loss by deposition.

B Diffusion to the Surface and Impaction

Generally, only particles in the size range greater than 10 microns have appreciable gravitational settling velocity. However, recent studies (Simpson 1961; Islitzer and Dumbauld, 1962) indicate deposition of micron and submicron particles upon the ground and vegetation may be considerable. Accounting for deposition of these smaller particles requires extension beyond the simple gravitational settling model.

Using the concepts presented by Chamberlain (1953) along with extensions reported by Healy (1957), a reasonable model can be developed. For these small particulates, deposition from the cloud to the ground is conceived as a process limited by meteorological diffusion and processes of impaction and sticking to objects on the ground rather than the settling of particles through the influence of gravity. It is visualized that the particles are brought through the boundary layer to the ground by the turbulent diffusion process. They then deposit on vegetation or other objects by inertial impaction and diffusion and stick by electrostatic forces, chemical attraction or other means. Investigations of this process in the neutral atmospheric condition assuming that the transfer coefficients for mass and momentum are equal indicates that the velocity of deposition should vary with wind speed. There is also evidence that the velocity of deposition changes with atmospheric stability. Data on the velocity of deposition of Iodine-131 at Hanford and from experiments conducted by the English have indicate indicated a value of about 2.7 cm/sec. Calculations based on the equivalence of mass and momentum transfer coefficients during neutral conditions yield about the same value. Measurements of the velocity of deposition of fission products from arc burned uranium have indicated that the velocity of deposition of these particles is considerably lower, on the order of 0.1 cm/sec.

Gifford and Pack (1962) recently published an evaluation of most of the experimental data obtained to date on deposition velocities of interest in nuclear safety studies.

Major conclusions were that the deposition velocities for active materials such as Iodine-131, sulfur dioxide, and ruthenium on flat plates or bare soil is less than 1 cm/sec and is between 1 and 3 cm/sec for deposition on vegetation. Also, it was concluded that the average deposition velocity of inert materials such as Cesium-137 and Strontium-90 on flat plates and vegetation is less than 0.1 and 0.1-0.2 cm/sec, respectively. These results are quite consistent, indicating that for particles of diameter less than 10-15 microns, the relative effects of impaction, diffusion, and absorption are more important than the widely varying gravitational settling velocities.

It is postulated that the particles are brought to the ground by turbulent diffusion where the iodine reacts with the vegetation to absorb strongly on the surface. The small smoke particles must depend on impaction or some other process to stick. Thus, although the rate of transfer of both materials to the ground was the same, the velocity of deposition was different because of the difference in retention.

Chamberlain (1953) bypasses these effects, and simplifies the problem by defining a deposition velocity V_g, as:

$$V_g = \frac{\text{amount deposited/cm}^2\text{ per sec}}{\text{volumetric concentration above the surface}} \qquad (10)$$

This definition may be expressed in the integral form as:

$$V_g = \frac{\text{total deposition/cm}^2}{\text{dosage/cm}^3} \qquad (11)$$

Thus, the deposition becomes:

$$w(x,y) = X\ V_g \qquad (12)$$

To account for depletion of material from the cloud, the equation must satisfy mass continuity principles such that:

$$\int_0^\infty \int_0^\infty X\ V_g\ dy\ dx = Q \qquad (13)$$

This equation is analytic in the first integration, but the resulting equation from combining (13) and (8):

$$1 = \int_0^\infty \frac{V_g}{\sqrt{\pi}\ \sigma_z\ \bar{u}} \exp -\frac{1}{2}\left(\frac{H^2}{\sigma_z^2}\right) d_x \qquad (14)$$

can be solved analytically if σ_z can be expressed in terms of x.

To account for cloud depletion resulting from the deposition, the constant source strength, Q, is replaced by a quantity Q_x, depending on x, which is defined so that:

$$\frac{\partial Q_x}{\partial_x} = -\int_{-\infty}^{\infty} w\ (x,y)\ dy \qquad (15)$$

Q_x is the total depletion to a distance x. Again, it is necessary to employ explicit relationships for the dispersion in order to derive specific deposition formulae.

C Removal by Rainfall - Rainout

The cleansing of the air by rain is an everyday experience and is one of the most important scavenging mechanisms in the atmosphere. In an analysis of rain scavenging of radioactive particulate matter from the atmosphere, Greenfield (1957) found that the direct interaction of raindrops and particles does not account for the efficient removal of material whose diameter is below approximately one micron. However, he was able to explain the removal of smaller particles by allowing them to mix with the water cloud before the rain starts. The small particles that are scavenged by coagulation are then placed in a position to be more efficiently removed by the rain.

Our present knowledge is still inadequate to provide anything beyond a suggestion of the scavenging processes in the atmosphere for such finely divided material as radioactive debris. Evidence from world-wide fallout studies suggests that the very small fission products become attached to the natural aerosol particles and then have a history in the atmosphere similar to that of the host. The time required for such a coalition to near completion is not known, but one would expect it to be as rapid as the coagulation with larger water droplets because of the relative differences in mean free paths. Junge (1958) suggests that the predominant cause of the modification in size-distribution of the stratospheric aerosols on the way down through the troposphere is the repeated cycle of condensation and evaporation of clouds, a process requiring considerable time. Thus, the scavenging mechanism for small particles is envisioned as cloud-droplet-scavenging coupled with later scavenging of the cloud droplets by larger raindrops. The amount of activity that will fall out as rain will depend upon the time of mixing of the contaminant and the cloud elements and the rate at which the cloud elements are swept from the cloud by larger raindrops.

Barad, Haugen, and Fuquay (1960) made estimates of some of these scavenging parameters. The effective scavenging constants, that is, the time required for the number of particles to decrease to 1/e of the initial value, for the contaminant activity in the presence of cloud droplets characteristic of stratus and cumulus cloud conditions were computed from Greenfield's curves, assuming that the activity was proportional to the volume of the particle. The cloud characteristics used by Greenfield compared favorably with later data reported by aufm Kampe and Weickman (1957) and were not altered. The calculated times required for one-half the activity from the air to enter the cloud droplets, that is, the scavenging constant ϕ, is shown in Table 2.

The amount of activity that will fall out as rain will depend upon the time of mixing of the contaminant cloud elements and the rate at which the cloud droplets are swept from the cloud by larger raindrops. This latter aspect was studied by Chamberlain using Langmuir's theory (1948) of the formation of raindrops by coalescence with smaller raindrops and Best's (1950) relationship between raindrop size and rainfall rate. Results of Chamberlain's study applicable to this type of scavenging are also summarized in Table 2. The scavenging of materials by clouds can only occur at heights at which clouds form. The heights of the various types of clouds vary within wide limits. However, scavenging by stratus clouds should be limited to 5000 feet and below, whereas scavenging by cumuliform clouds can occur at any height between 2000 feet and the tropopause.

Table 2. Parameters for Cloud-Droplet Scavenging of Particulate Cloud and Precipitation Scavenging of Cloud Droplets

Height interval	Cloud type	Rainfall rate (mm/hr)	Scavenging constant, ϕ (sec^{-1})	Elimination constant, (sec^{-1})
500- 5,000 feet	Stratus	0.5	5×10^{-6}	2×10^{-4}
5,000-35,000 feet	Cumulus	3.5	6×10^{-5}	1×10^{-3}

D Removal by Rainfall - Washout

Calculations for precipitation scavenging of materials released into the lower atmosphere usually consider only the interaction between the falling raindrop and the contaminant particles. However, the computed values correspond only approximately to the actual conditions, as the size of raindrops always show a spectral distribution. Best's curves contain mean values. Large deviations from this curve are found in individual rains with the extreme range in rainfall rate for a given mean drop size about a factor of two. In addition, the Langmuir theory is applicable to coalescence of waterdrops, with certain restrictions, and particle interception could be quite different, depending on the physical and chemical nature of the particle.

In an effort to clarify the scavenging processes in the lower layers of the atmosphere, a part of the total scavenging problem, Hanford meteorologists have been dispersing zinc sulfide into the air and measuring the amounts scavenged by both natural and artificial rain. Results thus far indicate a peak scavenging efficiency for raindrops of about 0.4 mm diameter and suggest a minimum scavenging efficiency for raindrops of 0.7-1.0 mm diameter for this material. This deviation from currently used theoretical calculations which predict a rather flat peak in efficiency for drops larger than 1.0 mm suggests that rainfall intensity as now related to rainfall type may not have as great an effect on washout values as previously thought.

In order to account for washout in the dispersion equations, we can write:

$$Q_r = Q \exp\left(- \frac{\Lambda x}{\bar{u}}\right) \tag{16}$$

where Q_r is the source strength correction for the scavenged material. Since rain removes material from the whole cloud depth, the process can be likened to radioactive decay in that the entire cloud is affected uniformly rather than preferentially near the ground, and the shape of the cloud distribution function is not altered. In this case, the concentration from a ground level source becomes:

$$x = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left(- \frac{\Lambda x}{\bar{u}}\right) \exp\left[- \left(\frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right)\right] \tag{17}$$

The amount of material deposited per second by rainout, w_r, is obtained by multiplying equation (17) by Λ and integrating with respect to z.

$$W_r (x,y) = \frac{Q \Lambda e^{- \frac{\Lambda x}{\bar{u}}}}{\sqrt{2\pi}\, \bar{u} \sigma_y} \exp\left[- \frac{y^2}{2\sigma_y^2}\right] \tag{18}$$

Values of Λ, the washout per second, are the subject of considerable speculation, and observational data are only now becoming available.

E Scavenging in a Pollution Episode

Meetham (1956) has discussed some interesting aspects of the London smog of 5-9 December, 1952, in which about 4000 people died above the normal death rate in Greater London.

Much can be learned by studying the physics of fogs themselves. City fogs of this episode magnitude have an estimated chance of recurrence of about 2% in any given winter. They are persistent, of limited area and volume, and relatively homogeneous; but not too well understood. You will recall that daily measurements of smoke and sulfur dioxide were being made at this time, but little if anything was known regarding concentrations of trace constituents, such as vanadium compounds, coal distillates, or aldehydes. Other materials, no doubt, present in the smog include sulphuric acid, carbon monoxide, hydrochloric acid, fluorides, and excess carbon dioxide. Consequently, the smog was greatly different in chemical composition from a relatively clear fog.

Meetham considered an area of 450 square miles in the London Basin containing about 8 million people. The fog covered the entire area to a height of about 500 feet. The temperature was near freezing so that the mass of air in this volume was 226 million tons. Material could diffuse from this volume upward at only a very slow rate because of the capping inversion above the fog. He estimated that the light and variable winds could have produced no more than one air change in about four days. Thus, he considered the region as a closed system in which to make estimates.

The air contained about 2,000,000 tons of liquid water as fog and 750,000 tons as vapor. The film of water on the ground, vegetation, and other objects was estimated to weigh 500,000 tons. The air also contained 380 tons of free smoke and 370 tons of free sulfur dioxide, not including any that was attached to or dissolved in fog droplets, or any other sulfur dioxide attached to smoke. The other impurities were not accounted for in the estimates.

About 70,000 tons of coal were burned each day in the region; releasing 1000 tons of smoke particles, 2000 tons of carbon dioxide, 140 tons of hydrochloric acid, and about 14 tons of fluorine compounds. Imperfect combustion of coal and motor vehicle exhaust contributed 8000 tons per day of carbon monoxide. In addition, 200,000 tons of carbon dioxide were emitted per day to be added to the 90,000 tons originally present.

Now, let us look at the heat balance. Essentially all of the heat from burning 70,000 tons of coal went into the fog volume and the heat equivalent of another 1400 tons of coal was added from the earth and surrounding air, which was warmer than the fog. This incoming heat was sufficient to warm the whole volume by 10°C per day, yet the temperature over the five days remained essentially constant. Fog behaves in the opposite way to a greenhouse so that radiation permitted this heat loss from the fog. If it had warmed up, the fog would have dissipated.

Another paradox is in the water balance. As in most persistent fogs, droplets of water are continually falling to the ground, and yet there is no reduction in the number of droplets in the air. In the London fog, the droplets had to fall through saturated air an average distance of 250 feet to reach the ground, a process would take about 6 hours. Thus, an estimated 800,000 tons of water per day left the fog and someway an equal amount replaced it.

Combustion of coal added some 35,000 tons per day and humans an additional 2000 tons. The remaining 763,000 tons per day, must have been evolved from evaporation from the ground. The heat coming up from the ground was sufficient to evaporate 18 million tons of water per day, so that it appears reasonable to assume that 4.3% of this heat was used for the evapoartion of water, which ultimately replenished the fog.

Thus, we have a somewhat plausible explanation of how fogs can persist in spite of apparently losing water and gaining heat.

Now let us examine the smoke balance. Smoke particles entered the fog at the rate of 1000 tons per day, and must have left at the same rate because a fairly steady equilibrium was maintained at 2.2 mg/m^3, or 380 tons in the whole region. The average smoke particles must have remained in the air for 380/1000 of a day or about 10 hours. Smoke particles are far too small to fall of their own weight as much as 250 feet in 10 hours. Meetham calculated that any smoke particle must collide with a fog droplet every couple of minutes or so and could have stuck to the droplet after some 4-10 hours. There was considerable dirt on the pavement which may have been smoke originally.

In the sulfur balance calculation, he assumed a rate of 2000 tons of sulfur dioxide per day entering the fog, and left at the same rate, maintaining a fairly steady equilibrium of 370 tons in the air. The average free life of a sulfur dioxide molecule would, therefore, be 370/2000 of a day or 4.5 hours. He considers that a few sulfur dioxide molecules were dissolved in the water on ground, vegetation, etc., but most of them were removed by the fog droplets, whose total surface area was about 170,000 km^2 compared with only 1160 km^2 of ground. The average sulfur dioxide molecule spent, perhaps, 0.05% of its time dissolved in fog droplets, moving freely in and out of them. Eventually, after a free life of 4.5 hours, during which about 8 seconds were spent within droplets, it became oxidized within a droplet, and remained fixed there as sulphuric acid. Six hours later, on the average, the droplet fell to the ground. If these calculations are correct, the mass of sulphuric acid in equilibrium in the fog must have been 800 tons. Its concentration was 4.5 mg/m^3 in the air, and, on the average, the fog droplets were a 0.4% solution of sulphuric acid.

Chlorine from coal entered the air in the form of hydrochloric acid at a rate of 140 tons per day. It was quickly dissolved in the fog droplets, remaining in the air an average of 6 hours. Its concentration was 0.2 mg/m^3 in the air or 0.02% in the fog droplets. Fluorine was present in about one-tenth of these amounts.

Oxides of carbon are not scavenged effectively and probably increased steadily throughout the period of fog. It was calculated that carbon dioxide reached a maximum concentration in the air of 0.4% by weight, or ten times its natural concentration. The concentration of carbon monoxide was calculated to be 180 mg/m^3 or 0.07% by weight.

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ANALYSIS OF AIR QUALITY CYCLES

James L. Dicke*

There are several important factors to be considered in evaluating a time sequence of atmospheric pollutant concentrations. The periodic recurrence of similar pollutant levels may result in a rather smooth curve with time and be termed cyclic or the concentration levels may appear to be random. In either case it is important to have enough background data to analyze the types of cycles which may exist. This background information should consist of data on the following items:

1. Source variables
2. Meteorological variables
3. Atmospheric reactions and removal mechanisms
4. Geometry of sources and samplers

I TYPES OF CYCLES

The first two areas are most important in determining air quality cycles. In general the most important types of cycles are the daily and annual. Together these cycles represent the day to day variations and the long term, 20-30 year, averages of pollutant levels. The day to day variations are principally due to meteorological variables, if the weekday to weekend variation in industrial activity is excluded. The long term variations in pollutant concentration can be attributed to source variables since the climatology of an area will remain relatively constant.

Figure 1 represents a generalized daily cycle. The two assumptions inherent in this figure should be remembered: continuous emission and elevated source. The curve represents the effects of two stability regimes

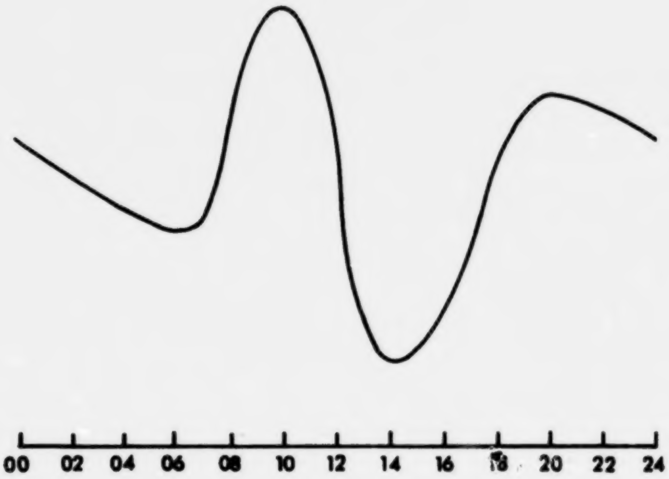

Figure 1. DAILY VARIATION OF GROUND-LEVEL CONCENTRATIONS FROM ELEVATED SOURCES

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in the lower atmosphere: stable conditions at night and unstable conditions in the afternoon. However, the cycles of many pollutants do not resemble each other as illustrated in Figure 2 for NO_2 and oxidant in California.(17)

The difference in daily curves between pollutants can best be understood by knowing the atmospheric reactions, methods of decay or half-life, and natural removal processes of the pollutants. Irregularities or peculiarities in pollutant cycles for specific locations can often be explained by being thoroughly familiar with both the meteorology and human activities of the community.

Annual or seasonal cycles of air quality also illustrate the inter-relationship of source and meteorological variables as shown in Figure 3.

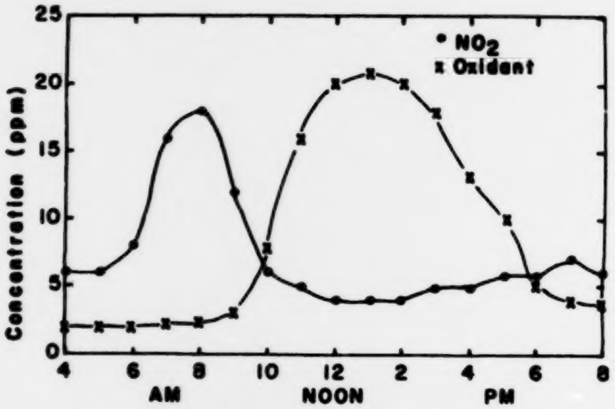


Figure 2. CONCENTRATION CYCLE OF NO_2 AND OXIDANT

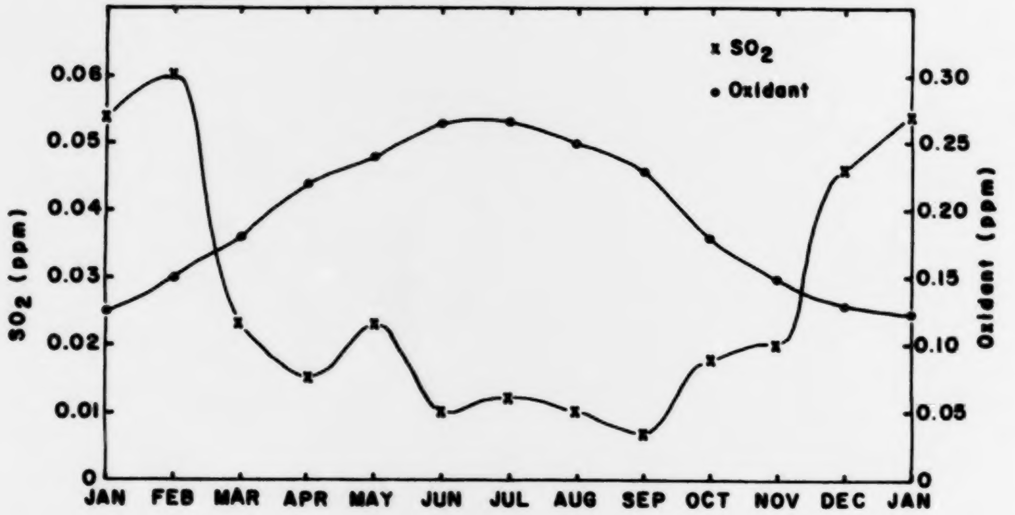


Figure 3. ANNUAL CYCLE OF SO_2 AND OXIDANT

If SO_2 emissions from industrial processes are considered fairly constant during the year, the annual curve of SO_2 concentration may be explained in terms of temperature or heating degree days.(12) Monthly averages of daily maximum oxidant concentration in California are primarily dependent on the amount and duration of sunshine and also high temperatures.(11) The annual cycle of maximum mixing depth in the atmosphere, wind speed, frequency of temperature inversions, and temperature will usually provide valuable information on interpreting the annual cycle of air quality in a community. Annual or seasonal cycles of air quality are more likely to be influenced by the geometry of the sampling network than are daily cycles. In most regions this is a function of meteorology, too, because the seasonal wind regimes may change by 180°.

II SAMPLING TIME

When planning an air pollution survey or pollutant sampling program, it is important to decide which of the two types of cycles, or both, is most important. Is the long-term effect of pollution being studied or are short-time peaks, e.g., 5 minutes, in concentration important? The answer will aid in determining both the sampling time and equipment to be used.

Short-time or spot sampling generally will not reveal pollutant cycles but may be used to determine the source of a particular pollutant or the contribution of a specific source to the general pollution level of the area.

Continuous sampling at fixed locations is best when the purpose of a study is to:

1 Determine the general level of pollution.

2 Determine improvement achieved by control measures.

3 Determine correlations between weather and different pollution levels.

4 Determine cycles of air pollutants with respect to the specific city.

III AVERAGING TIME

Another very important decision to be made concerns averaging time. This is the time duration over which either single air pollution samples are measured or a series of samples are grouped together to obtain a single measurement. Daily cycles, of course, cannot be ascertained from two, 12 hour samples, and compiling an annual curve from 20 minute samples is tedious and time consuming. Averaging time for samplers should be determined by:

1 Objectives of the study

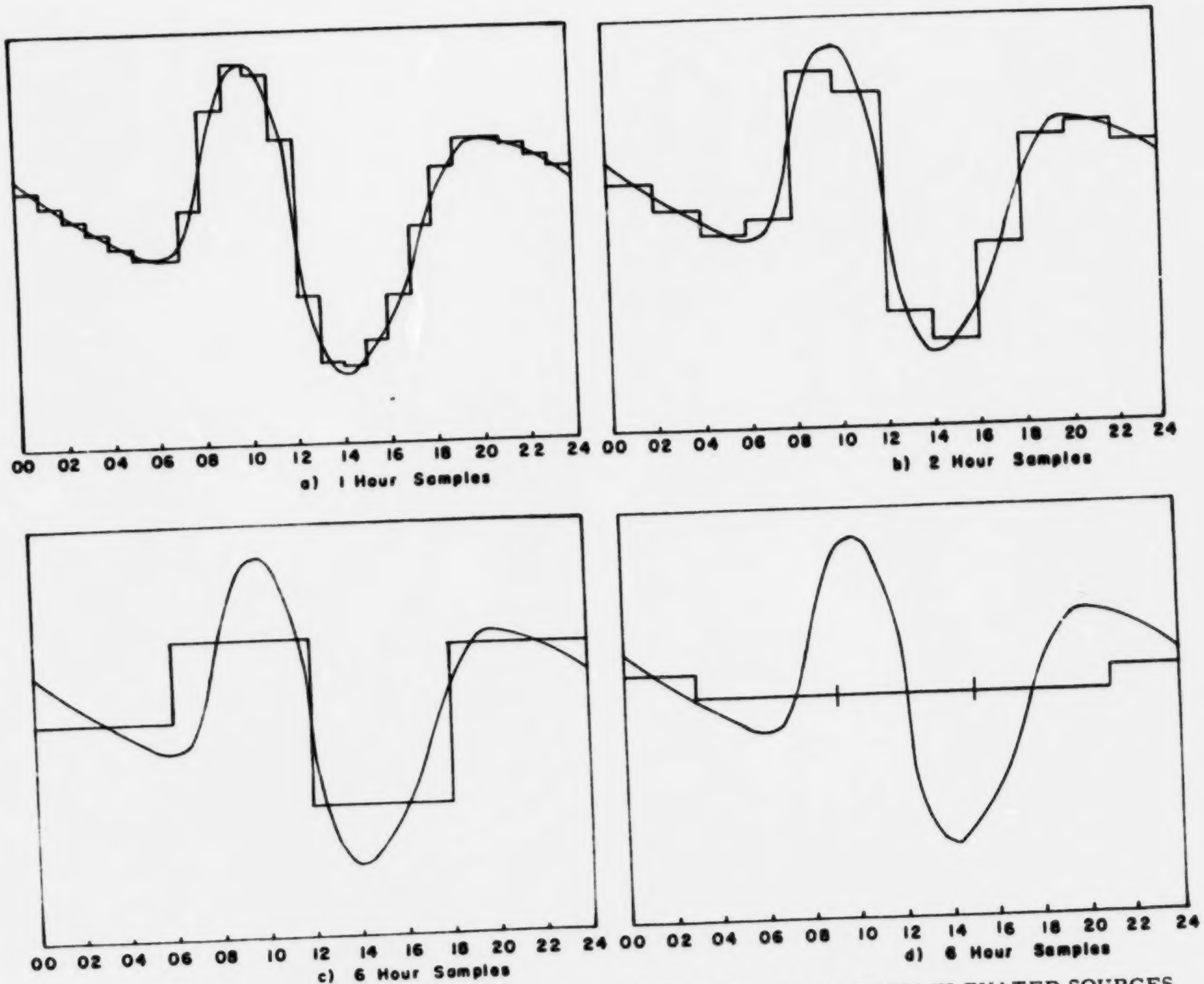
2 Equipment limitations

3 Analytical threshold values

4 Facilities and manpower for analysis

Starting and ending time of samples becomes important when averaging times are more than two hours. Figure 4 illustrates the difference in average concentration when comparable length samples are taken beginning at different times of the day. A knowledge of pollutant variation may enable the averaging time to be lengthened from 5 to 20 minutes or 20 minutes to an hour depending on whether or not very short time peaks of concentration are important.

The effect of averaging time on measured SO_2 concentrations for several cities (one sampling station per city) is shown in Figure 5, as taken from reference 19. Relationships for other pollutants will vary, depending on source distribution and reactions in the atmosphere.



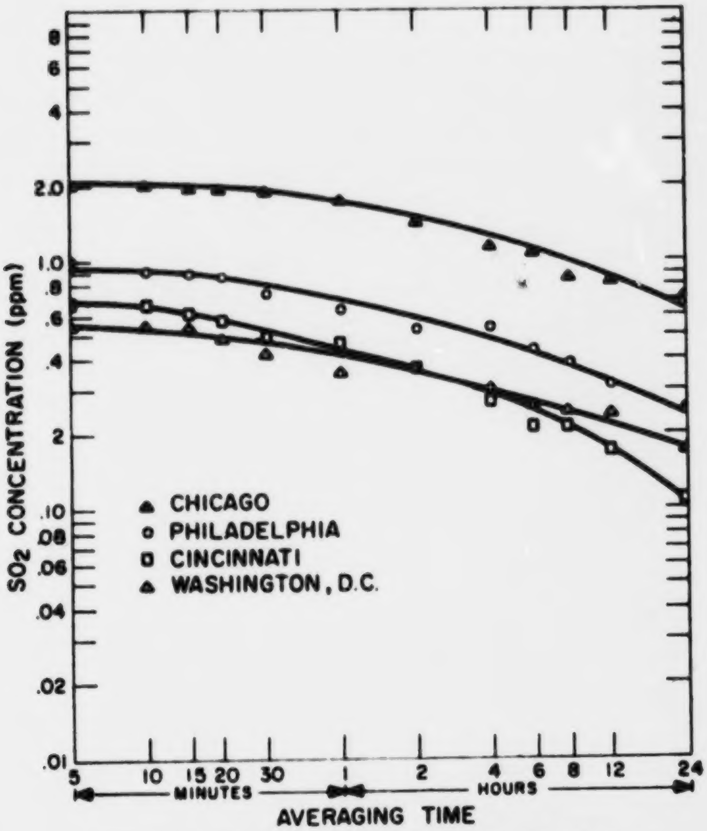
a) 1 Hour Samples

b) 2 Hour Samples

c) 6 Hour Samples

d) 6 Hour Samples

Figure 4. DAILY VARIATION OF GROUND-LEVEL CONCENTRATIONS FROM ELEVATED SOURCES



MAXIMUM SULFUR DIOXIDE
CONCENTRATION FOR SELECTED
AVERAGING TIMES
DECEMBER 1962 - JANUARY 1963

FIGURE 5

IV METHODS OF ANALYSIS

The methods of analysis used to evaluate and interpret data depend primarily on the aim of the pollution study. Three main considerations are:

1 Amount and type of data available.

2 Representativeness of the number of samples taken.

3 Required accuracy of the results.

Evaluation of data can be divided into two broad, and not mutually exclusive categories:

1 Comparative

2 Statistical

Examples of the first method are surveys during different periods of the year, improvement due to process changes or corrective measures, and comparisons of one locality with another to illustrate relative degrees of pollution. Sophisticated statistical methods would not be required in these cases.

Statistical methods are necessary to gain a deeper understanding of multiple influences on concentration variations. Statistical treatment of data aids in the evaluation of relative influences of a number of parameters, the significance of differences in concentration levels, and the correlation of two or more series of data.

One of the first steps in analysis should be to plot the data against time. This will emphasize any cycles present and also the length of period or times of daily maximum and minimum concentration A few anomalies in the plot will occur, but for comparative evaluation these usually are not significant. Elementary statistical parameters which characterize the data and can easily be computed or approximated are the mean; or average value, the range or amplitude of values, the median or value which divides the data into an upper and lower half, and mode or most frequently observed value.

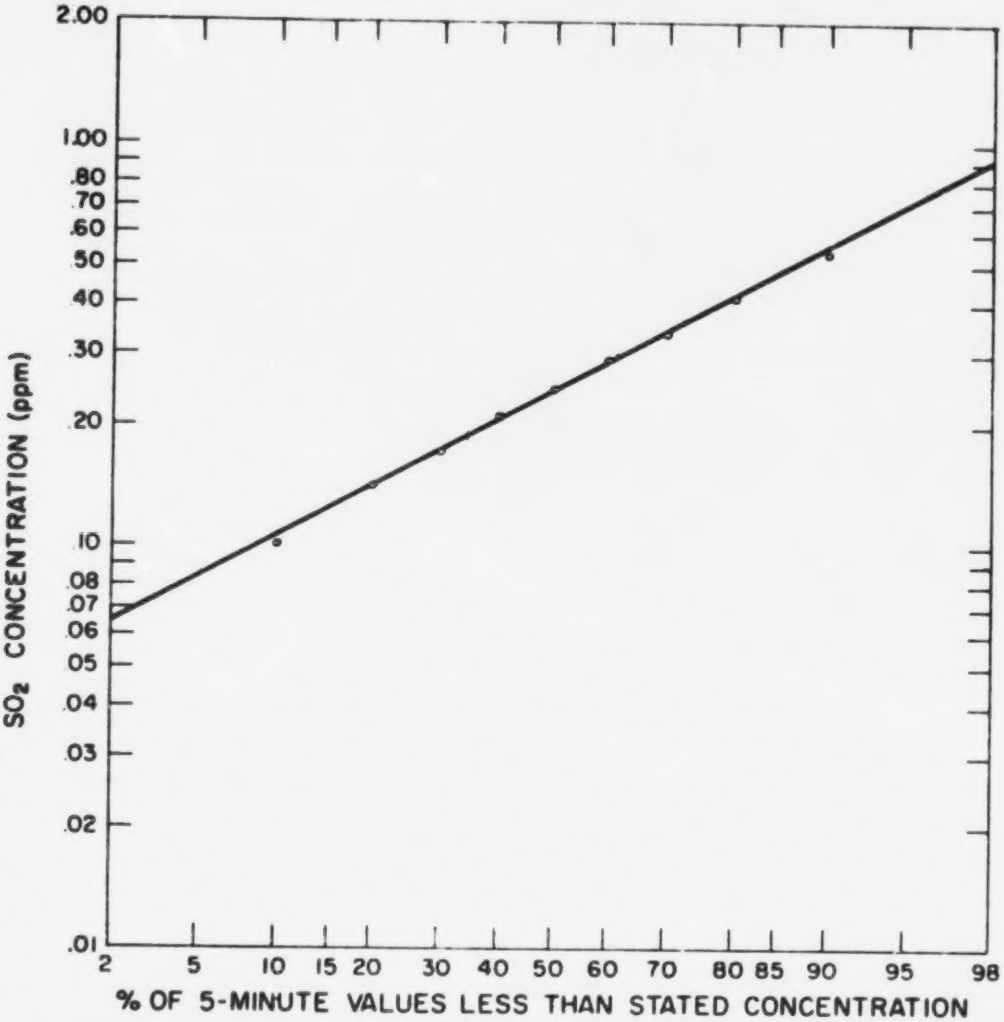
Other plots of the data versus meteorological and source variables should be made to indicate where relationships occur which need further investigation. Plots which approximate straight lines are usually best candidates for future analysis. If short sampling time data, e.g., 5 minutes, have been averaged to give hourly values, the ratio of peak 5 minute concentration to the mean hourly value will give a qualitative idea of atmospheric stability during the sampling period. Under neutral stability conditions, 5 minute peak concentrations about twice the hourly mean can be expected. Under unstable conditions, 5 minute peak concentrations about four to five times the hourly mean will occur. If wind direction data are available, evaluation should be by frequency distribution in tabular form. The per cent frequency of a given concentration is entered with the corresponding wind direction that occurred at the time the samples were taken.

A common form of data representation used in air pollution work is the "cumulative frequency distribution" in which the logarithm of pollutant concentration is plotted as a function of frequency of occurrence. Frequency of occurrence is expressed as "percent of values equal to or less than a stated concentration". Typical data is shown in Figure 6.(19)

Cumulative frequency distribution of individual pollutants will exhibit different characteristics. This is illustrated by the data of Figure 7,(20) wherein the frequency scale has been changed to "percent of values equal to or greater than a given concentration".

In situations wherein the same pollutant is emitted from ground-level and elevated sources, the cumulative frequency distribution curve, especially for short survey periods, may take the form shown in Figure 8.(21)

A few of the parameters, in addition to those mentioned above, which are calculated for a statistical study include the standard deviation, variance, correlation and autocorrelation coefficients, and regression equation coefficients. Statistical analysis is best accomplished by computer methods.



CUMULATIVE FREQUENCY DISTRIBUTION OF 5-MINUTE MEASUREMENTS OF SULFUR DIOXIDE CONCENTRATION CHICAGO, ILL., DECEMBER 1962 - JANUARY 1963

FIGURE 6

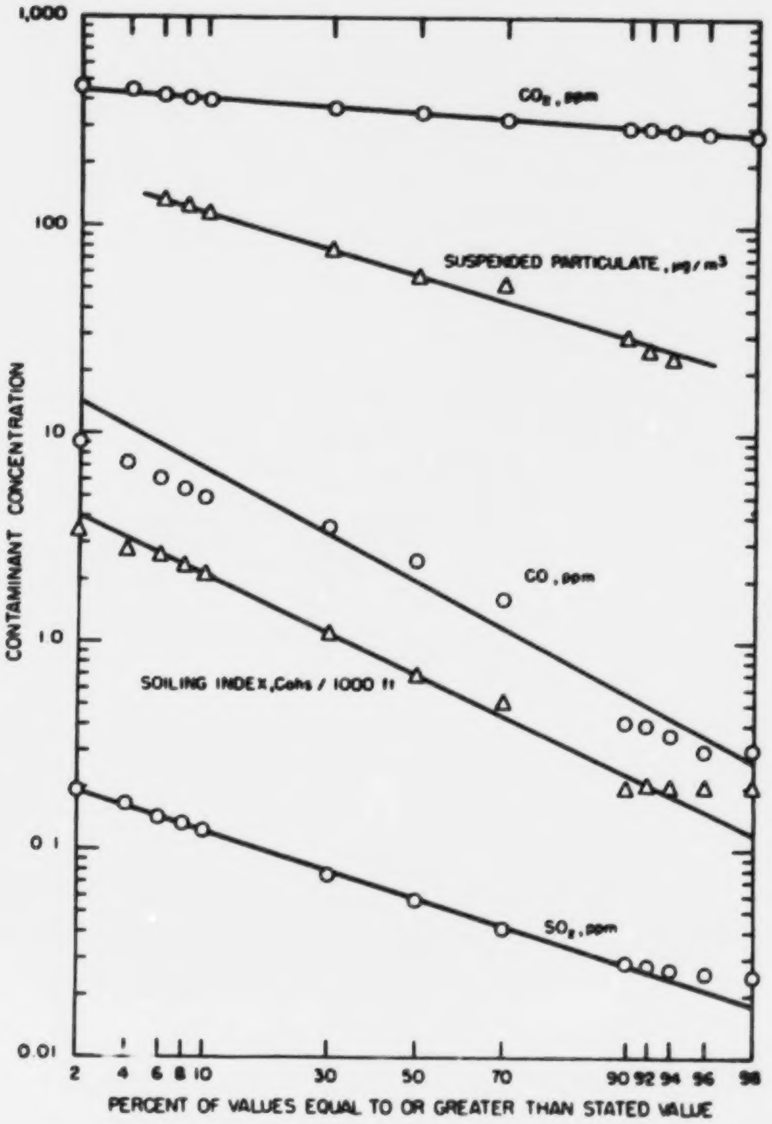


Figure 7. CUMULATIVE FREQUENCY DISTRIBUTION OF CONCENTRATIONS OF VARIOUS CONTAMINANTS

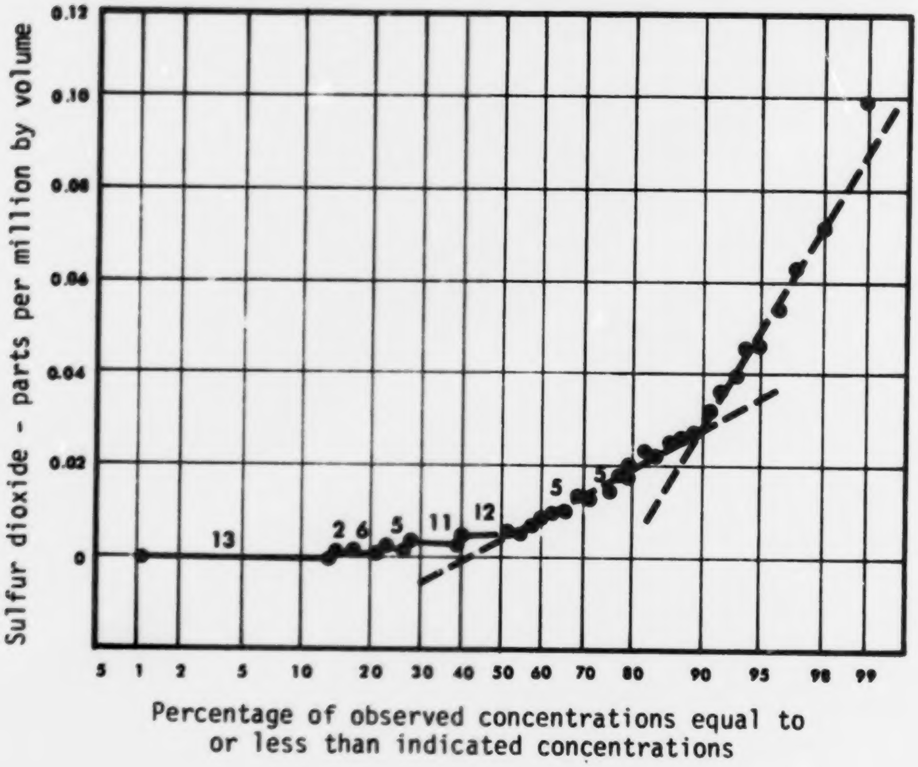


Figure 8. DISTRIBUTION OF OBSERVED SULFUR DIOXIDE CONCENTRATION - STATION A SEPTEMBER 5 - 13, 1961

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SECTION SIX

METEOROLOGICAL INSTRUMENTS

- General Instrumentation Requirements
- Meteorological Instruments
- Exposure of Instruments
  - Exposure of Surface Instruments
  - Exposure of Instruments on Towers or Stacks
  - Exposure of Airborne Instruments

GENERAL INSTRUMENTATION REQUIREMENTS

Ronald C. Hilfiker

"Precision Instruments", "Handsome Walnut Console", "High Degree of Accuracy", "Rugged Construction", "Black Crackle Finish", "Corrosion Resistant", and "Ultra-sensitivity" are among the many descriptive phrases used in instrumentation catalogs. Some of these attributes should be considered in detail, while others may be stereotyped as "window dressing".

The purchase of an instrument requires the consideration of two classes of requirements:

1. General Instrumentation Requirements
2. Specific Objective Oriented Requirements

There are many instrumentation requirements that will obviously depend on the specific objectives of the study that the instrument is to support. There are, however, a number of instrument requirements that should be considered before the purchase of any instrument. It is the purpose of this section to describe these general requirements so that a buyer will be able to distinguish between the instrumentation attributes that are important, and those that are only "window dressing".

RELIABILITY

Reliability is possibly the most important criterion for an instrument in continuous use. Regardless of how accurately an instrument is calibrated and read, it must be reliable to give reproducible results.

ACCURACY

Accuracy is defined as the closeness of the instrument output reading to the true value of the parameter. The qualifications of an accurate instrument are as follows:

1. It is properly calibrated under known conditions
2. It has characteristics that are unchanging with time
3. The reactions of the instrument (dynamic response) to changes in the measured parameter are known to within the limits of error requirements

PRECISION

Precision is generally defined as the degree of closeness of a series of readings of an unchanging parameter. There often is confusion between the terms accuracy and precision. One way of clarifying their meanings is through the use of the "bulls eye" analogy. Figure 1 depicts this analogy.

SENSITIVITY

Sensitivity is defined as the smallest change in the measured variable that causes a detectable change in the output of the instrument.

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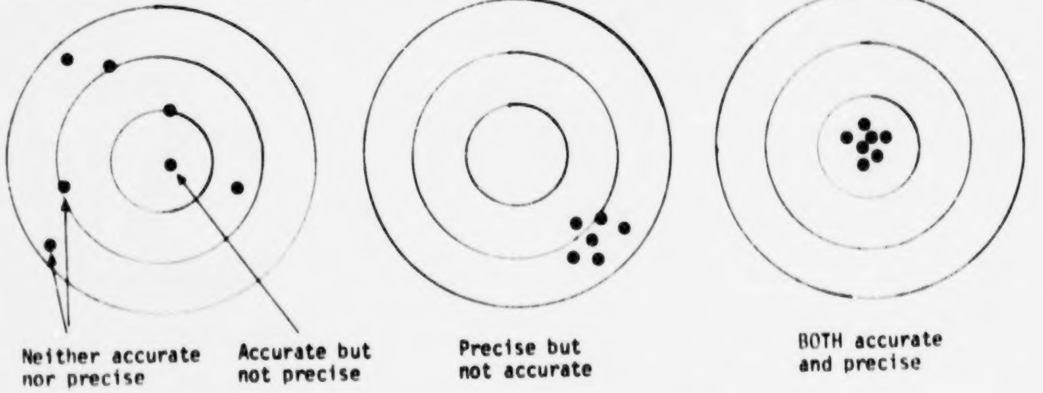

Figure 1.

SIMPLICITY

The lack of instrumentation experience among most observers makes this attribute a must for most meteorological instrumentation. The qualifications of a simple instrument are as follows:

1. Operational adjustments of the instrument should be simple
2. A simply written SOP manual should accompany the instrument
3. Adjustments that are not intended to be made by the purchaser should require a special tool

DURABILITY

Obviously, an instrument should be durable enough to survive vibrations and shock encountered in transportation, rough handling, etc. A meteorological instrument, in addition, should be able to perform reliably in all seasons of the year, and in a smoggy and corrosive atmosphere.

CONVENIENCE

Convenience of operation is definitely a must for an operational instrument. As a general rule, an instrument that is simple to operate is also convenient to operate.

Other requirements such as time constants, damping ratio, etc. are objective oriented, and will be covered in a later section.

METEOROLOGICAL INSTRUMENTS

Ronald C. Hilfiker

I INTRODUCTION

Measurement of atmospheric variables that affect the diffusion and transport of air pollutants is of necessity in nearly every air pollution investigation. Suitable measurements may be available from existing instrumentation at Weather Service city offices, airport stations, or from universities or industries with meteorological installations. Frequently, however, existing instrumentation does not give detailed enough measurements, is not representative of the area in question, or does not measure the variables desired (such as turbulence) and additional instruments must be operated.

Of primary importance in air pollution meteorology is the measurement of wind, both velocity (direction and speed) and the turbulence of the wind. The stability of the lower layers of the atmosphere in which the pollution diffuses is important and may be determined from an analysis of the turbulence characteristics of the atmosphere or the temperature lapse rate.

Of secondary importance is the measurement of humidity (which may affect atmospheric reactions), temperature, precipitation (of importance in washout of pollutants), and solar radiation (which affects photochemical reactions in the atmosphere). Particularly for research studies, it may be desirable to measure meteorological elements affected by pollutants, mainly: visibility, solar radiation, and illumination (radiation in the visible region).

II WIND MEASUREMENTS

A Surface Instrumentation

1 Wind Speed

Generally, wind speed sensors are broken down into the following categories:

- a Rotational Anemometers
  - 1) Vertical Shaft
  - 2) Horizontal Shaft
- b Pressure Anemometers
  - 1) Flat Plate Type Anemometer
  - 2) Tube Type Anemometer
- c Bridled Cup Anemometer
- d Special Types
  - 1) Hot Wire Anemometer
  - 2) Sonic Anemometer
  - 3) Bivane
  - 4) UVW Anemometer

Pressure anemometers, hot wire and sonic anemometers have enjoyed extensive use in research type operations, but they all have disadvantages which have prohibited their use in operational type situations such as air pollution surveys. The rotational type anemometers are the most common type of wind speed sensor in use today mainly because they are the only types that satisfy all of the following desirable operational features:

- a Essentially linear relationship between the sensor output and the wind speed.
- b Calibration is unaffected by changes in the temperature, pressure or humidity of the atmosphere.
- c Able to measure a wide range of wind speeds (<2 to >200 mph [.9 to >90 m/s]).
- d Long term calibration stability. The calibration often is unchanged after 10 years continuous operation.
- e Output of the sensor is easily adapted to remote indication.
- f Recording of the wind speed data is easily adaptable to either analog or digital form.

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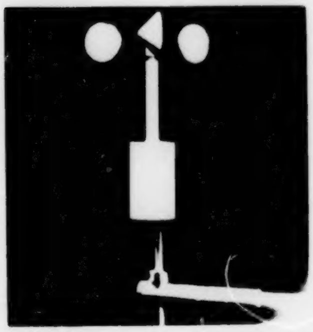
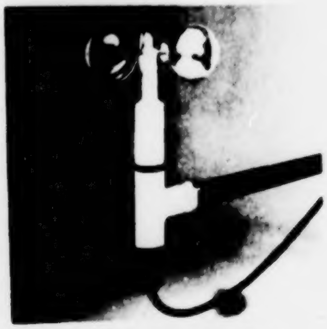
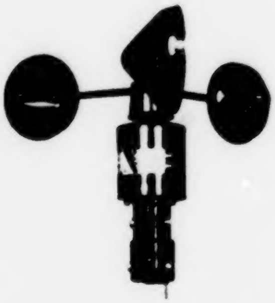


Climet Inst. Co. (a)

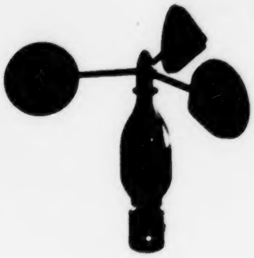


R.M. Young Co. (b)

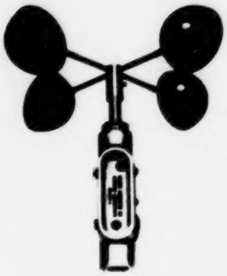


Belfort Inst. Co. (c)

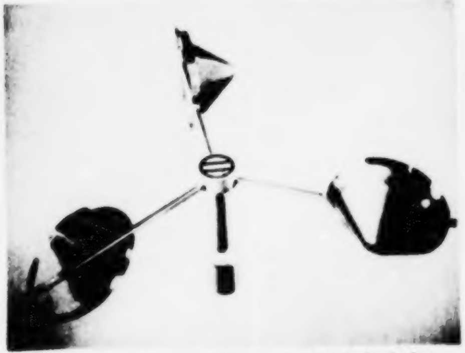
Henry J. Green Co. (d)



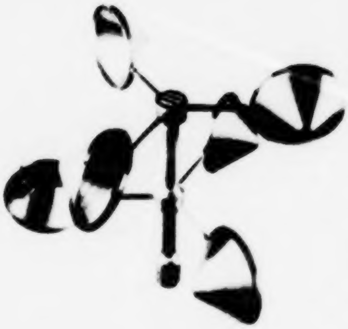
Electric Speed Indicator Co. (e)



Science Associates Inc. (f)



Teledyne-Geotech (Bkmn & Whtly) (g)



Teledyne-Geotech (Bkmn & Whtly) (h)

Figure 1 - Cup Anemometers

g Generally require extremely little maintenance.

Types

a Rotational Anemometers

1) Vertical Shaft - a cup anemometer revolving about a vertical shaft is probably the most commonly used anemometer in use today. The most common of the cup anemometers are the 3-cup types shown in Figure 1. Traditionally, anemometers have only had to yield average wind speeds for use in the support of aviation and weather forecasting operations. Sensors such as those in Figure 1c and 1e were developed with durability as the primary requirement. These cups are about 10 cm. in diameter, with a moment arm of about 42 cm.

These anemometers, due to their large mass, have a relatively high starting speed (that wind speed at which the cups first begin to rotate or reach the manufacturers accuracy specifications) of about 3 mph (1.4 m/sec). This factor of high mass combined with a long moment arm will also produce a high moment of inertia which tends to cause the cups to indicate erroneous wind speeds under gusty conditions. Not only will the instantaneous readings be in error, but because the cups accelerate faster than they decelerate, the mean speed indicated may be slightly higher than the true speed.

With the advent of environmental concern, an anemometer was needed that would measure light winds, which are of great importance in air pollution meteorology. Also, to support turbulence and diffusion studies, an anemometer was needed that would approach giving an instantaneous response to wind speed fluctuations. Lightweight anemometers such as those in Figure 1a, 1b, and 1g were developed for such purposes. To provide accuracy at low speeds and greater sensitivity, these small 3-cup anemometers are lightweight in construction (plastic or very thin aluminum) and employ a relatively short moment arm. In addition, friction has been reduced by utilizing miniature ball bearings and special type transmitters. The cups are generally 5 cm. in diameter and have a moment arm of about 7 cm. The result of these design considerations is more accurate instantaneous and average windspeeds.

An attempt at further reducing the starting speed is shown in Figure 1h. This cup wheel design, employing six staggered cups, yields a greater surface area exposed to the wind. This factor decreases the starting threshold from .75 mph (.35 m/s) for the standard 3-cup of Figure 1g) to .4 -.5 mph (.2 - .25 m/s). This design also produces a more uniform torque around the entire shaft revolution.

2) Horizontal Shaft - The second most commonly used wind speed measuring system is one that has a propeller on the end of a horizontal shaft that is oriented into the wind by a vane on the opposite end of the shaft. A propeller anemometer is shown in Figure 2, and several pro-

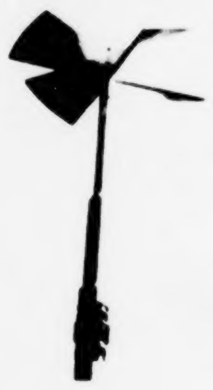


Figure 2 - Propeller Anemometer

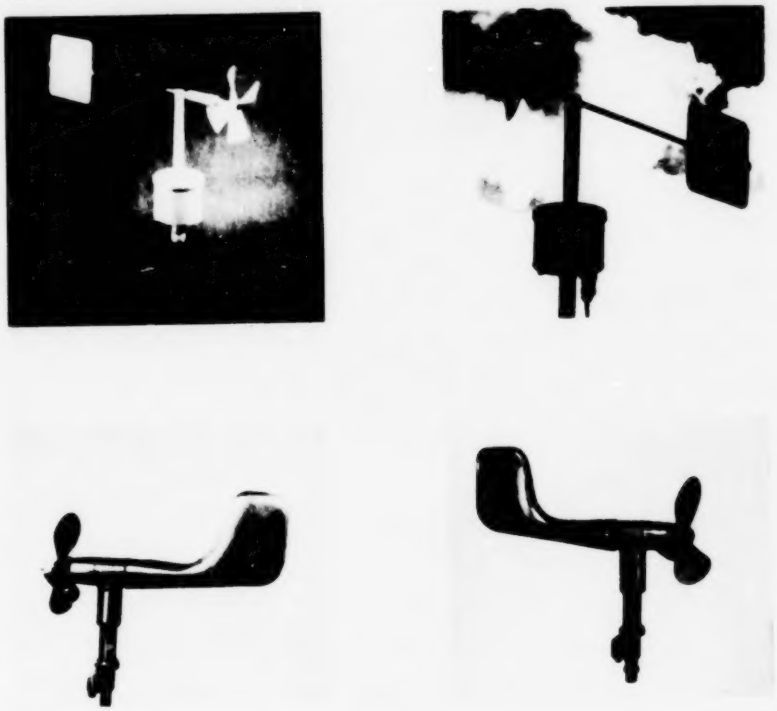


Figure 3 - Propeller-vanes

peller-vanes are shown in Figure 3. These propellers are usually helicoidal in design with the rate of rotation of the propeller being linearly proportional to the wind speed. As with the cup anemometers, the propeller anemometers generally fall into two design categories:

i. Those designed with durability as a prime consideration (Figure 3c,d)

ii. Those designed with sensitivity as a prime consideration (Figure 2, 3a,b)

    The more sensitive propeller anemometers utilize lightweight aluminum or plastic as blade material, and generally employ either 2 or 4 blades. The 2-bladed propellers (Figure 3b) have starting speeds of about .4 - .7 mph (.2 - .35 m/s), while the 4-bladed propellers have a threshold of about .3 - .5 mph (.15 - .25 m/s).

The more durable propeller anemometers use heavy gauge plastic or steel in the blade construction. Because of their relatively heavy mass, the 3-blade design of Figure 3c, d have higher starting speeds of about 2.5 - 3 mph (1.2 - 1.5 m/s).

The sensitivity argument developed earlier for the cup anemometers also applies to propeller anemometers. However, because of the helicoidal design of the blades, the number of blades has no effect on the torque uniformity. The design produces a uniform torque independent of the number of propeller blades.

b Special Types

1) **Propeller Bivane - These anemometers are capable of measuring the magnitude of the wind vector and will be discussed more fully in the wind direction sensor portion of this section.**

2) **UVW Anemometer - Another sensor configuration that yields the wind vector and its fluctuations is the UVW anemometer. Figure 4 shows one type manufactured by R. M. Young Company. In this sensor configuration, a propeller anemometer is mounted in each principal axis (thus the name UVW), and each yields the component wind vector in that axial direction. This anemometer has found limited operational use because of the sophisticated data reduction that is necessary to convert from an output of 3 wind speeds to a vector magnitude and direction.**

   The UVW anemometer has, however, enjoyed easy application to those situations where the 3 component vectors are the only desired output, or where data reduction is accomplished through the use of a computer.

   As with all sensors of the propeller type, serious error is introduced during periods of heavy precipitation, and with this particular propeller configuration there is some mutual interference error with certain wind directions.

2 Wind Speed Measuring Transducers

The most common aerodynamic sensor for the measurement of wind speed is the cup or propeller. The wind speed measuring transducer must convert this cup or propeller rotation to an energy form that is easily transmittable. The energy form is usually electric and the transducer is commonly one of four types.

a D.C. Generator

Small, permanent field generators are used that have an output that is linearly proportional to the rate of turning of the cup or propeller and hence is linearly proportional to the wind speed. The main disadvantage of D.C. generators is the relatively high starting or threshold speeds. The brush and bearing friction combine to produce a lower limit to the threshold speed of about 1 mph (.5 m/s) on the most sensitive systems. The brushes on these generators usually need servicing only about once a year under continuous use. On some of the more sensitive sensors the unit is sealed and it is recommended that the unit be sent to the factory for servicing or replaced completely.

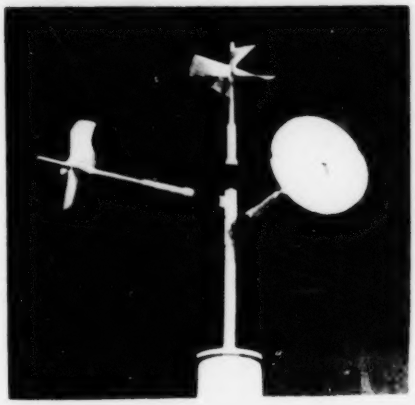


Figure 4.- UVW Anemometer

Figure 5 illustrates a typical D.C. generator (brushes not shown) from the sensor of Figure 1e. The output from this transducer can be recorded directly on any D.C. galvanometer recorder.

b A.C. Generator

In an attempt to lower the threshold speed by eliminating brush friction, some manufacturers are using A.C. generators instead of D.C. generators. A.C. generators reduce the friction considerably and eliminate brush and commutator maintenance. A.C. generators are available with either two, four, six or eight-pole permanent magnet rotors. The larger the number of poles, the more pulses are available per shaft revolution, producing a smoother record.

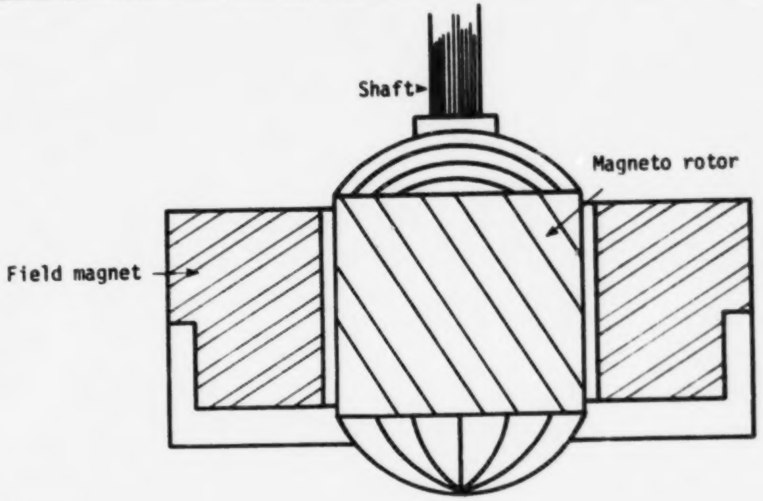


Figure 5 - D.C. Tachometer Generator

The largest disadvantage of the A.C. generator is associated with the number of pulses per shaft revolution. These pulses must be rectified by a modifying transducer (rectifier) in order to have a suitable energy form for recording. Low wind speeds generate a low frequency of A.C. pulses and normal rectifiers do not function properly with a low frequency input. Thus, spurious oscillations may be produced at low wind speeds. Therefore, to obtain wind speeds below about 2 m/sec (4 mph) some sort of electronic correction is needed.

This disadvantage defeats the purpose of reducing the friction and has therefore resulted in a minimal use of this type of transducer.

c Interrupted Light Beam

Further reduction in friction with accompanying lower threshold speed and quicker response can be accomplished with the use of an interrupted light beam (light chopper) transducer. This transducer employs either a slotted shaft (Figure 6) or a slotted disc (Figure 7), a light source and a photocell or photo-diode. The cup or propeller rotates the

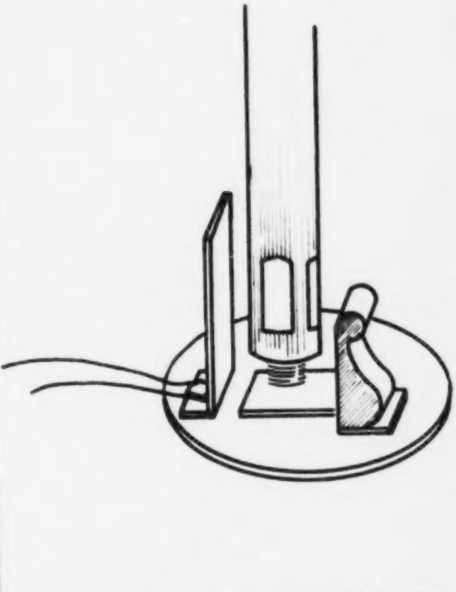


Figure 6 - Slotted Shaft Light Chopper

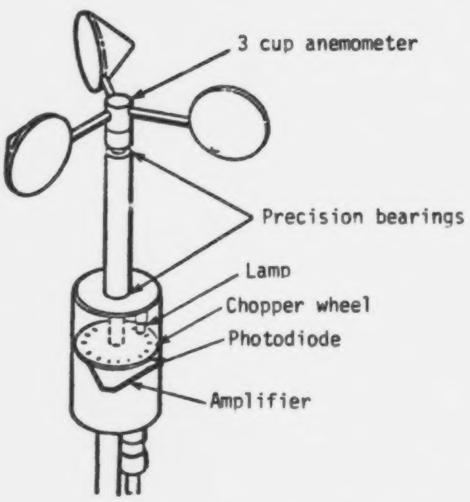


Figure 7 - Slotted Disc Light Chopper

slotted shaft or disc and a pulse is created each time a slot allows light from the source on one side of the shaft or disc to fall on the photocell on the other side of the shaft or disc. The larger the number of slots in the shaft or disc, the smoother will be the output, especially at low wind speeds. The out put from the transducer is handled in the same manner as the output from the A.C. generator. The large number of slots (about 100) prevent spurious oscillations in the output at low wind speeds. The sensors of Figure la, g utilize this type of transducer.

d Mechanical - contact type

All of the measuring transducers mentioned so far produce an analog signal. There are circumstances where the desired output might be total miles of wind passage instead of a time plot of wind speed. Under these circumstances, a mechanical-contact transducer is used. In this type of transducer, the anemometer shaft is connected through one or more gears to a cam or similar device that opens or closes a contact after the passage of a pre-determined amount of air. This contact closure can operate a readout device such as an event marker pen on a recorder. Recorders, such as the one shown in Figure 8 can be furnished with circuitry to provide a pen actuation for each 10, 100 or 1000 contact closures in the transducer. If the average wind speed is desired instead of length of wind passage, the number of contact closures are determined for a given time increment and, knowing the miles or meters of wind passage for each contact closure, the average wind speed over the given time increment is easily determined.

Figure 8 - Event Marker Recorder

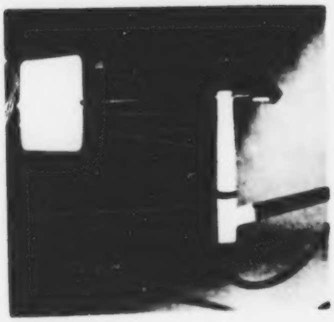
3 Wind Direction

a Type

1) Flat Plate Vane

Typical flat plate vanes are shown in Figure 9a, b, c, d, g, i, k, and l. The term flat plate refers to the tail shape which is simply a flat plate. The flat plate can take on a number of different shapes and be made out of a number of different materials.

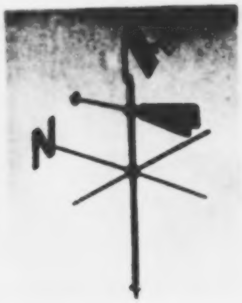
Climet Inst. Co. (a)



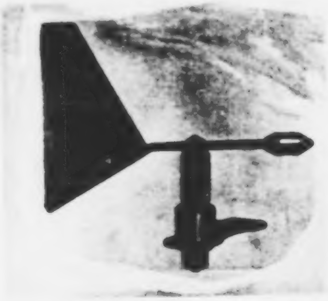
R.M. Young Co. (b)

Belfort Inst. Co. (c)

Science Associates Inc. (g)

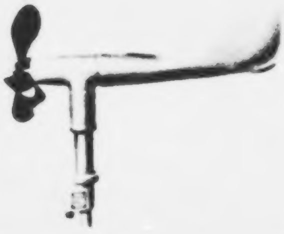


Epic Co. (h)



Epic Co. (i)

Bendix Co. (m)



Belfort Inst. Co. (n)

Teledyne-Geotech (l)

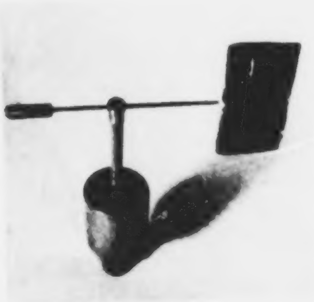
Wong Lab. (d)

Electric Speed Indicator Co. (e)

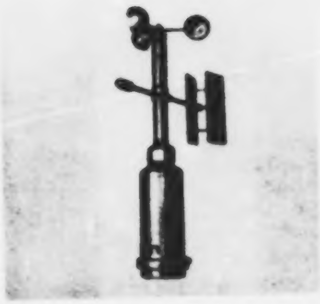
Science Associates Inc. (f)

Teledyne-Geotech (j)

Teledyne-Geotech (k)



Raim Inst. Co. (o)



Epic Co. (p)

● Figure 9 - Wind Vanes

As with wind speed sensors, the material used in constructing the wind vane will generally determine the proper use of the vane. Vanes made out of heavy gauge metal or plastic such as in Figure 9 should be used only for obtaining average wind direction. The large mass creates a high moment of inertia which will give, under certain conditions, a much higher indication of wind fluctuations than actually exists.

The lightweight sensitive vanes of Figure 9a, b, d, k and l have tails made out of thin gauge aluminum or plastic or molded expanded polystyrene. The counterweights are also close to the center of rotation. This design creates a highly sensitive vane that can be suitably used for turbulence or other fine analyses of the wind trace.

2) Splayed Vane

Typical splayed vanes are shown in Figure 9e, f, h, and p. In this type of vane, two flat plates are joined at a small angle (usually about 15°) at one end of the horizontal shaft. This design came about through experimentation that showed that the splayed vane followed small changes in wind direction better than the flat plate. However, the increased mass incurred by two flat plates makes this type of vane unsuitable for anything but the measurement of average wind direction.

The splayed vane of Figure 9 has, mainly because of its durability and reliability, found widespread use in its role as the main wind direction sensor for the National Weather Service. Therefore, it should be noted that wind direction data obtained from a National Weather Service should be used only as an indication of average wind direction.

3) Aerodynamic Shaped Vane

This type of wind vane is shown in Figure 9j, m, n, and o. The aerodynamic shaped vane has an airfoil cross section. This type of vane has been shown to produce up to 15% more torque for certain ranges of attack angles than a flat plate vane of similar physical dimensions.

This type of design, as with the splayed vane, incorporates more mass than the flat plate vane and therefore produces a higher moment of inertia, yielding a poor dynamic performance. An aerodynamic wind vane that has found wide-spread use in air pollution studies is shown in Figure 9m, n. This device is commonly called an "aerovane". It should be remembered that its dynamic performance is inferior to the sensitive vanes of Figure 9a, b, d, κ, l, and the use of the data gathered by the "Aerovane" should reflect this fact.

4 Wind Direction Measuring Transducers

The measurement of wind direction consists of converting the angular position of the wind vane to an energy form that can be transmitted easily. The system of Figure 9h has direct readout obtainable simply by observing the sensor. This system is, at best, very crude.

More advanced wind direction systems usually employ one of 3 types of measuring transducers.

a Potentiometer system

b Synchro-motor system

c Commutator system

Types

a Potentiometer System

The most common and inexpensive way of converting the angular position of the vane to an electrical signal is through the use of a potentiometer system such as the one shown in Figure 10.

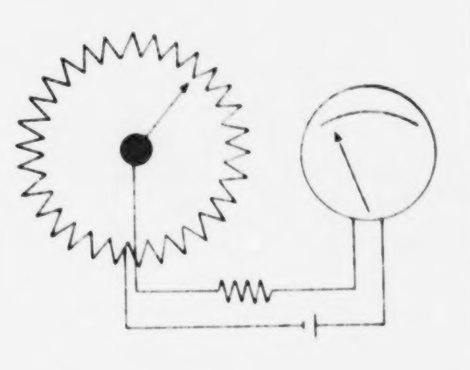


Figure 10 - Potentiometer Transducer System

In this system the shaft of the vane is attached to the wiper arm of the potentiometer. The swinging vane therefore produces a continuously varying voltage that can be recorded on a recording voltmeter or dial indicator. With proper calibration, the recorded voltage gives a direct reading of the angular position of the vane.

The biggest drawback to this system is the unavoidable discontinuity in the potentiometer. If the wind direction is oscillating about a direction corresponding to this gap (usually north), the voltage output will oscillate between the maximum and minimum value producing what is commonly called "chart painting". With the recorder pen swinging from one end of the chart to the other, the record produced is, at best, very confusing.

There are some types of recorder pen movements available that circumvent this problem. Double contact potentiometers with dual pen recorders produce a trace along each edge of the chart when the wind direction corresponds to the gap. Figure 11 illustrates a chart record of this type. In newer recorders, there is available electronic circuitry and a 540° chart that can keep the pen trace in the central portion of the chart. Figure 12 illustrates a chart record of this type.

Wire potentiometers present a problem of excessive wear produced as the contact moves along the wires. The life expectancy of wire-wound potentiometers is only about 6 months-1 year under continuous operation. Recent advances in this area have produced a conductive plastic potentiometer.

The life expectancy of these potentiometers is about 50×10^6 oscillations, or about 3 - 5 years, under continuous operation. The linearity

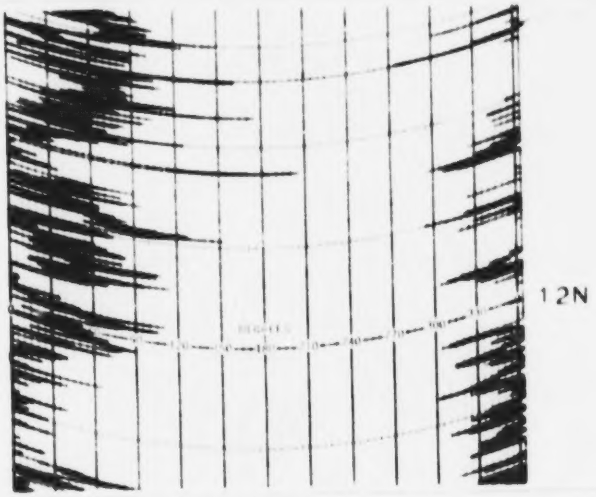


Figure 11 -
Dual Pen Recorder Chart

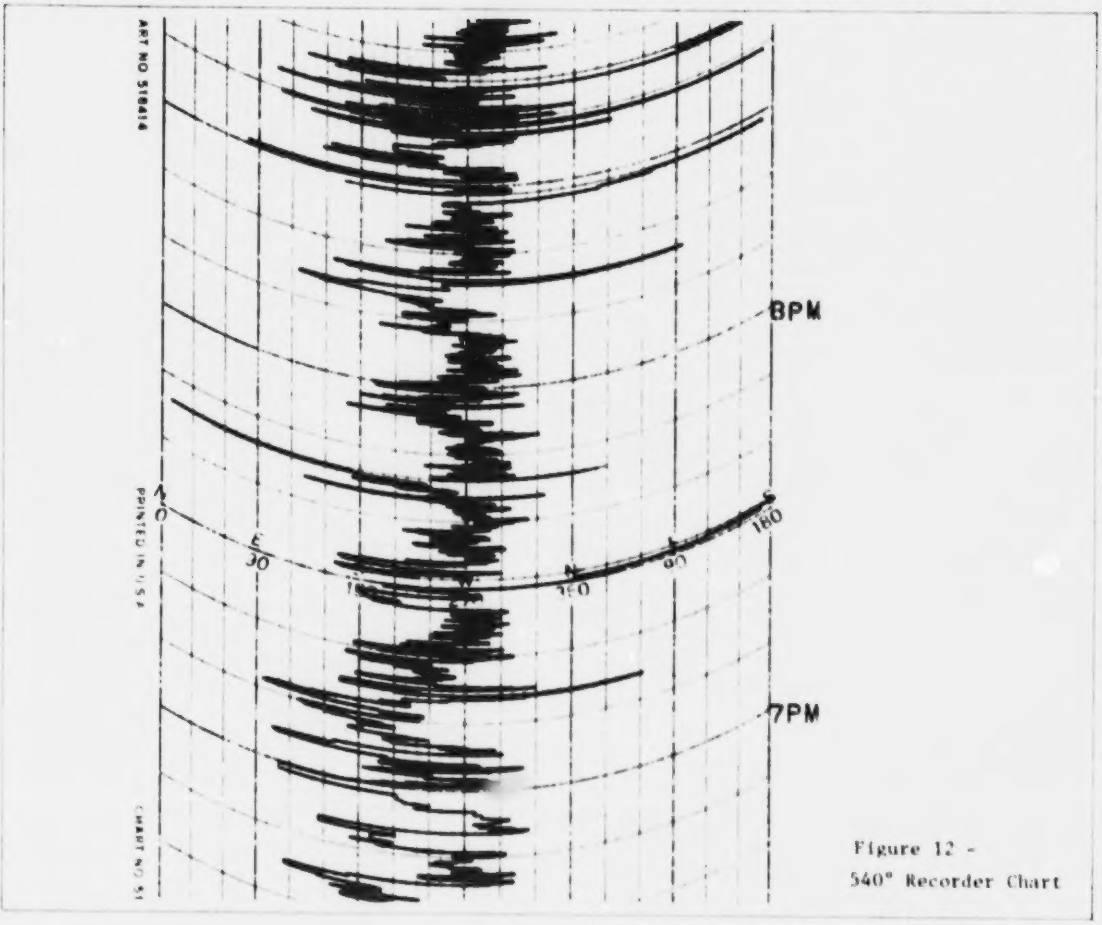


Figure 12 -
540° Recorder Chart

of these devices is about .5%.

The use of micro-potentiometers produces the lowest movement of inertia of any of the direction transducers available today. This fact has led to their widespread use in the sensitive wind vanes that are noted for their good dynamic performance.

b Synchro-motor System

This transducer system consists of two synchronous motors wired as shown in Figure 13.

They are commonly known as "Autosyn", "Selsyn" or "Synchrotie" systems.

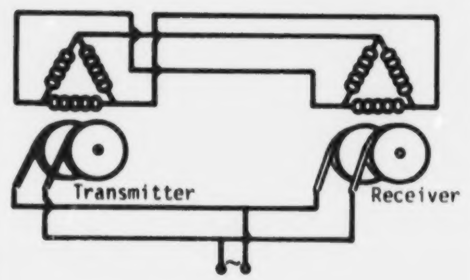


Figure 13 - Synchro-motor System

In this mode, any movement by the shaft of the transmitter will be duplicated by the shaft of the receiver motor usually to an accuracy of about 2°, provided the lead resistance is kept to a maximum of 20Ω.

The vane shaft is coupled to the shaft of the transmitter motor and the shaft of the receiver motor is coupled to a recorder pen or some other read-out indicator. Therefore, any vane movement is duplicated by a movement of the dial needle, recorder pen etc., and with proper calibration and alignment, a direct indication of wind direction is obtained. There is no discontinuity in the movement as with the potentiometer. This transducer system is usually coupled with a 540° chart recorder system or a dial indicator to produce an analog trace of wind direction. The system also lends itself readily to a dial indicator display. The only disadvantage of this transducer system is the relatively large movement of inertia of the motor assembly. This produces a poorer dynamic performance than the micro-potentiometer system and limits their use to the mere rugged vane types such as the aerovane sensors of Figure 9m, n.

c Commutator System

The wind direction transducers discussed so far produce an analog signal that can be converted to an analog chart trace. The commutator transducer system shown in Figure 14 produces contact closures which can be used to activate lights, event marker pens etc.

In this system, the vane shaft is coupled to a unit that has two brush type contacts, (A and B), spaced 22 1/2 degrees apart. These brushes make contact with one or two of the 8 conducting sectors (C) that are spaced 45° apart and correspond to 45° of wind direction. When both brushes contact the same sector, the direction indicated is one of the 8 compass points, eg., N, NE, E. If the brushes are contacting two of the sectors, the indicated direction corresponds to an intermediate direction, such as NNE, ENE, ESE, etc. Therefore, direction indication to 16 points can be obtained with this system.

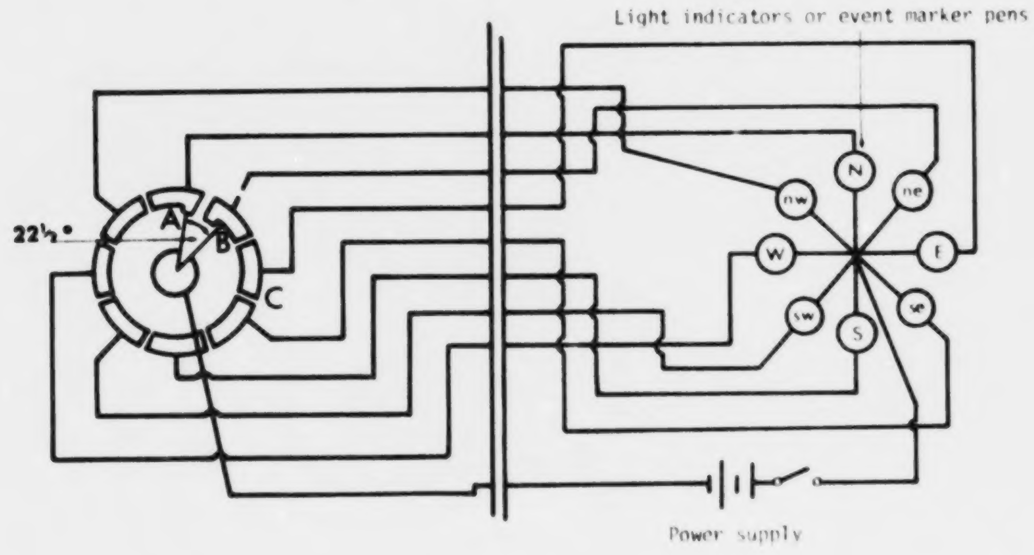


Figure 14 - Commutator Transducer System

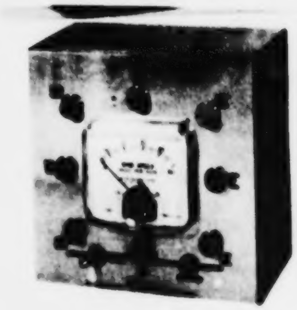


Figure 15 - Commutator System Visual Display

Figure 16 - Commutator System Chart Record

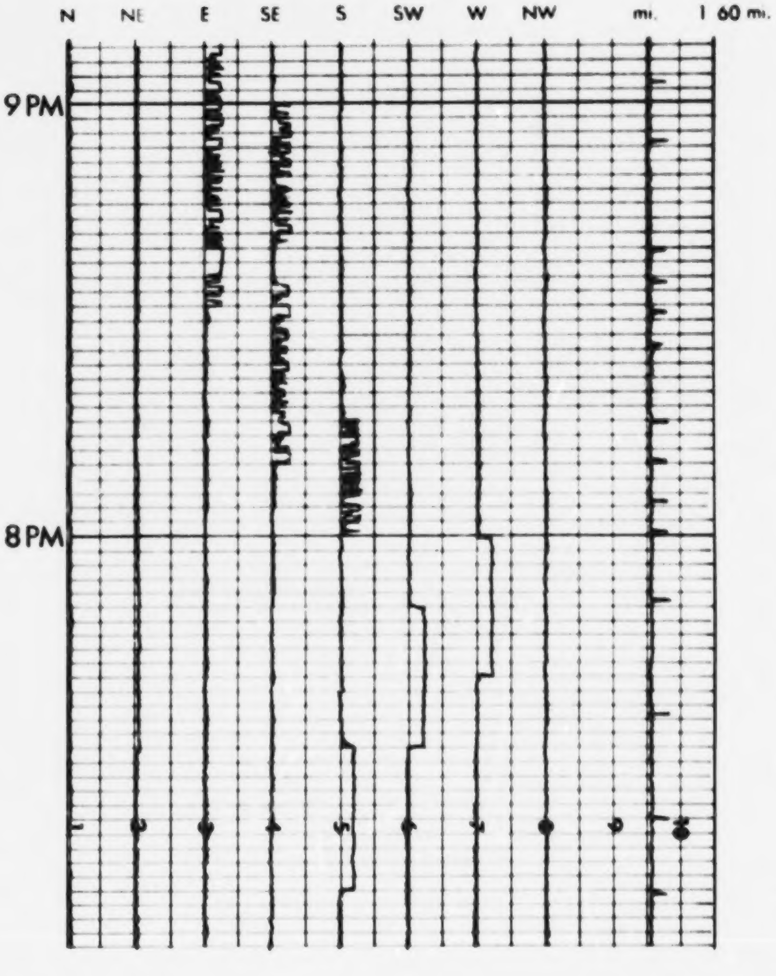


Figure 15 shows a visual display utilizing lights. An intermediate direction would be indicated by the activation of two adjacent lights.

Figure 16 illustrates a chart record produced by this type of transducer system. An intermediate direction would be indicated by the activation of two adjacent pens.

The friction inherent in the commutator transducer as well as the crude method of display make this transducer most applicable to operations involving only the acquisition of average wind direction.

Special Types

a Bi-directional Vanes (Bivanes)

This type of instrument is designed to rotate around a vertical axis to measure the azimuth angle of the wind, as does a conventional wind vane. It also can move in the vertical to measure the elevation angle of the wind. Because the vertical motions of the atmosphere are frequently of a different character than the horizontal motions (anisotropic turbulence), measurement of both the horizontal and vertical motions are desirable. This is particularly true under stable conditions when the vertical motion is almost absent, but horizontal changes in wind direction may be appreciable. Micro-potentiometers are usually used to produce an analog record of both angles. The total wind speed can be measured by replacing the counterweight with a propeller anemometer. Figure 17 shows two typical anemometer bivanes.

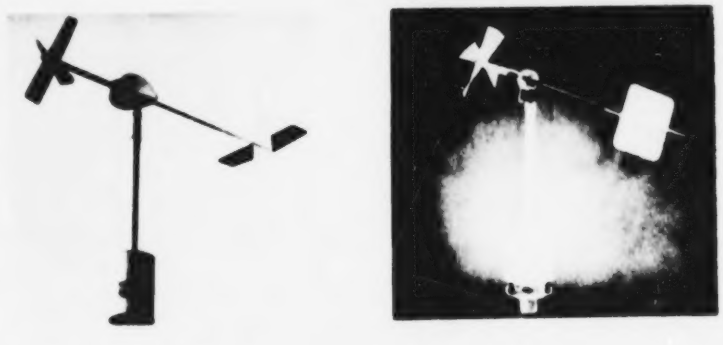


Figure 17 - Anemometer Bivanes

B Airborne Sensors

Fixed location wind velocity sensors measure the wind at a fixed height as it varies with time. Most airborne sensors are used to average wind velocity through a given depth of the atmosphere at a particular time.

1 Pilot Balloon (pibal)

This method of measuring wind velocity uses a gas-filled free balloon (Figure 18) which is tracked visually through a theodolite. The theodolite is an optical system used to measure the azimuth and elevation angle of the balloon.

a Single Theodolite Pibals

When only one theodolite is used, the balloon is inflated to have a given amount of free lift. The elevation and azimuth angles are used with the assumed ascent rate to compute wind directions and speeds aloft. A theodolite is shown in Figure 19.

b Double Theodolite Pibals

By this method, the ascent rate of the balloon is not assumed, but calculated from the elevation and azimuth angles of the two theodolite observations taken simultaneously.

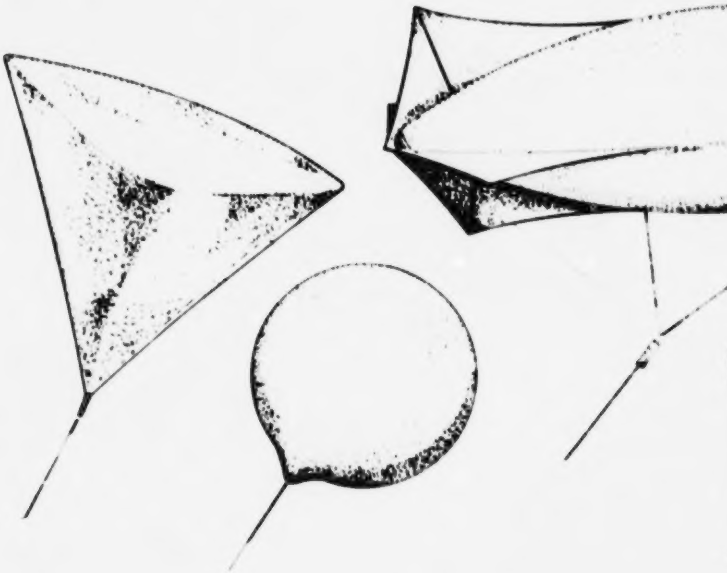


Figure 18 - Meteorological Balloons
(L to R - Tetroon, Pilot Balloon, Kytoon)

Figure 19 - Theodolite

The two theodolites are set a known distance apart (the baseline). Two types of pilot balloons frequently used reach 3000 ft. within 5 minutes and 8 minutes respectively after release. If detailed structure of winds with height is to be determined, readings of azimuth and elevation angle must be read every 15 or 30 seconds.

2 Rawinsonde

This method of measuring wind velocity aloft also uses a gas-filled free balloon, but it is tracked either by radio direction finding apparatus, or by radar. The former method is the most frequently used in the U.S. The radio transmitter carried by the free balloon is usually used to transmit pressure, temperature and humidity information to the ground (radiosonde). The radio direction finding equipment determines the elevation angles and azimuth angles of the transmitter. The height is determined by evaluation of the temperature-pressure sounding. Using radar the slant range is available for determining height. Soundings taken with this type of equipment are made on a routine basis for supporting forecasting and aviation activities. The ascension rate of these balloons is on the order of 1000 feet/minute, so they do not yield as detailed information on winds in the lowest part of the atmosphere as is desired for many air pollution meteorological purposes.

3 Rocket Smoke Plumes

A system using a cold propellant, recoverable rocket to emit a vertical smoke trail to an altitude of 1200 feet has been developed. (Gill, Bierly, and Kerawalla). This smoke trail is photographed simultaneously at short time intervals by two cameras 2000 feet from the launch site and at right angles to each other. The difference in position of the smoke trail from two successive photographs is a measure of one component (north-south for example) of the wind and can be determined at any number of heights from ground level to 1200 feet. Another system has been reported by Cooke (1962).

4 Constant Level Balloons

Unlike the previous airborne sensors for wind velocity which obtain average measurements through a vertical layer, constant level balloons are used to determine the trajectory or path of an air parcel during a given time interval. In order to maintain a constant altitude (more accurately to fly along a constant air density surface) the balloon must maintain a constant volume. A tetrahedron shaped balloon (tetroon) of mylar has been used for this purpose (Figure 18). These have been tracked visually and by radar. (Angell & Pack, 1960).

III TEMPERATURE LAPSE RATE

The vertical structure of temperature gives an indication of the stability and turbulence of the atmosphere.

A Temperature Difference Measurements

One method of estimating the vertical structure of temperature is by measuring the difference in temperature between sensors mounted at different heights. This, of course, gives an average condition between any two particular sensors.

1 Heights of Sensors

Because of the pronounced influence of the earth's surface on the atmosphere's temperature, it may be desirable to measure temperature difference at closer intervals near the ground than at higher levels. For example, a 300 foot tower might have sensors at 5 feet, 25 feet, 50 feet, 100 feet, 200 feet, and 300 feet. The height differences at the upper levels should be about equal so that the height of inversions may be determined. Radio and television towers are good supports for temperature difference sensors (as well as wind sensors) and stations usually are willing to allow sensors to be mounted upon their towers. Of course, sensors must be kept below the level of the transmitting antenna.

2 Sensors

Resistance thermometers of copper or nickel may be used for temperature difference systems. Thermo-couples of copper-constantan or iron-constantan also make reliable sensors. Resistance thermometers and thermocouples do not have to be frequently calibrated and may be expected to provide good service for 10 to 20 years if properly installed. Thermistors are not generally recommended because they may be quite variable from unit to unit and they may require recalibration more frequently than the other two types of sensors. Rapid response is usually not desired in measuring temperature differences. Rather, averages on the order of 5 minutes are desired. If the sensors are 1/2 to 5/8 inch in diameter, they will respond slowly enough to give an average temperature.

3 Shielding and Ventilating

Guidelines for the exposure of temperature sensors are covered in the following section.

4 Recorders

Generally multiple point (10 or 20 points) recorders are used for recording temperature differences. Thus, one recorder may be used for the entire system. The recorder is connected to one sensor for about 30 seconds, prints and then switches to another level. If a 6 minute cycle is used (print for each level every 6 minutes) there will be 10 readings every hour and an hourly average may easily be obtained by adding the 10 readings and shifting the decimal point 1 place. The sensors are usually wired so that the temperature differences are obtained directly rather than determining the temperature at each level.

B Balloon-borne Sensors

Temperature sensors may be lifted by either free or captive balloons. By this method, temperature, not temperature difference, is measured.

1 Radiosonde

The method of radiosonde (radio-soundings) observations is used routinely for temperature, pressure and humidity soundings of the upper air. A free balloon carries the sensors and a radio transmitter aloft. Cycling from sensor to sensor is by means of an aneroid barometer and consequently is a function of pressure. Observations are normally made twice daily at 0000 GCT and 1200

GCT at approximately 70 stations in the contiguous U.S. The ascent rate of the balloon is about 1000 ft/minute. Generally only 4 to 6 temperature readings are recorded within the lower 3000 feet so the vertical temperature information is not too detailed. It is still of considerable use when more detailed information is not available.

2 T-Sonde

This system consists of a temperature sensor and radio transmitter which is carried aloft by a free rising balloon. The main difference between this system and the radiosonde system is that only temperature is measured. Ten to twelve measurements are taken within the lower 3000 feet of the atmosphere, thus giving more detailed structure of temperature with height.

3 Tethered Kite Balloon

Using a captive balloon system to make vertical temperature measurements has the advantages of complete recovery of all components of the system, and as detailed a temperature sounding as is desired may be made by control of the level of the sensor. A balloon having fins is much easier to control and gives greater lift in slight winds than a spherical balloon. See Figure 18. Most kite balloons can be used in winds less than 15 knots. For air pollution meteorology purposes, the light wind periods are of greatest interest anyway. Because of hazards to aircraft, prior permission from the FAA is required for flights exceeding 500 feet above ground.

For additional precautions when using captive balloons, the reader is referred to the section on "Exposure of Airborne Instruments".

Several methods of relaying the observations to the ground have been used.

a Wiresonde

Using this system, a resistance thermometer is carried aloft by a kite balloon whose mooring cable contains wires connecting the sensor with a wheatstone bridge on the ground which is used to measure the resistance.

b Modified Radiosonde Transmitter

Another system uses a modified radiosonde transmitter to measure temperature and humidity. The signal is transmitted to the ground receiver and recording equipment by the same method used in the radiosonde. Cycling from one sensor to another is by a battery driven timing device. The temperature sensor is shielded from the sun by the styrofoam plastic and is aspirated by a small motor driven fan. The mooring of this system is by nylon cable marked at intervals to indicate the height of the sensor.

C Aircraft Borne Sensors

In some cases, light aircraft or helicopters have been used for obtaining temperature lapse rate measurements. Although there are complete systems commercially available for this method of temperature lapse rate measurement, one can use standard temperature sensors (thermisters, resistance thermometers, etc.) and recorders as long as the exposure guidelines presented in the next section are followed.

IV THE MEASUREMENT OF SECONDARY METEOROLOGICAL PARAMETERS

A Precipitation

Because large particles and water soluble gases may be removed from the atmosphere by falling precipitation, measurements of this element may be needed. Chemical or radioactive analysis of rain water may also be desired.

1 Standard Rain Gauge

The standard rain gauge consists of a metal funnel 8 inches in diameter, a measuring tube having 1/10 the cross-sectional area of the funnel, and a large container of 8 inches diameter (Figure 20). Normally precipitation is funneled into the measuring tube. The depth of water in the tube is measured using a dip stick having a special scale (because of the reduction in area). Measurements with this instrument, since they are made manually, give only accumulation since the last measurement.

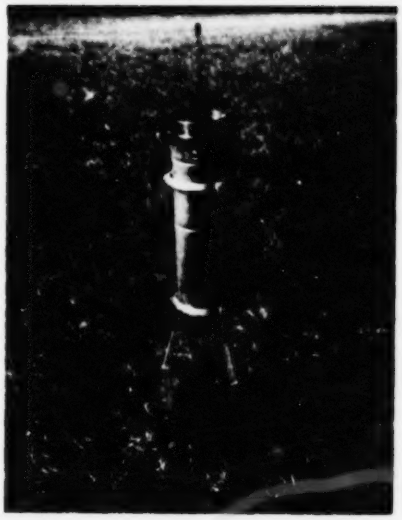


Figure 20 - Standard Rain Gauge

2 Recording Rain Gauge

The recording (or weighing) bucket rain gauge does give detailed time resolution of occurrence, and amount of precipitation as a strip chart, with one revolution per day, is used. The gauge consists of a bucket (to hold the precipitation) on a scale, which weighs the precipitation and moves the pen arm, recording the total accumulation on the chart, calibrated in inches. (Figure 21)

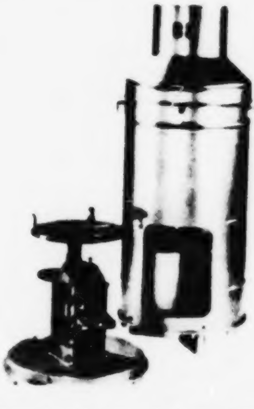


Figure 21 - Weighing Bucket Rain Gauge

3 Tipping Bucket Rain Gauge

This precipitation gauge has a bucket with two compartments beneath the collecting funnel. (Figure 22). When one side of the bucket collects a given amount (usually 0.01 inch) of precipitation, the bucket tips and empties the precipitation, collecting the next portion in the other side. The bucket movements are recorded on a chart. The number of bucket movements and the time they occur indicate the rainfall amount and rate. This type instrument is not suitable for measuring snow.

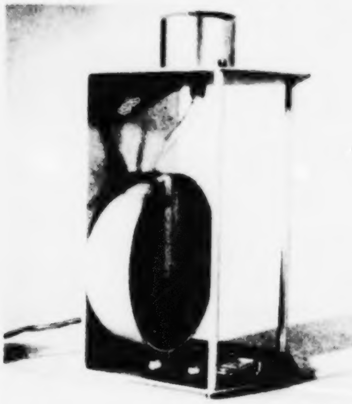


Figure 22 - Tipping Bucket

4 Precipitation Collector

For research purposes, it is desirable to analyze rainfall as to its chemical and radioactive constituents. Since it is desirable to include only precipitation samples, and not material that may fall into the collector during dry periods, a collector which opens only during periods of precipitation has been developed. The sensor (Figure 23) has two sets of adjacent wires. A raindrop falling between the wires completes an electrical circuit which removes the cover from a polyethylene container. A small heat source dries the sensor so that the circuit will be broken when precipitation ceases and also so that dew will not form and open the collector. This instrument is illustrated in Figure 24.

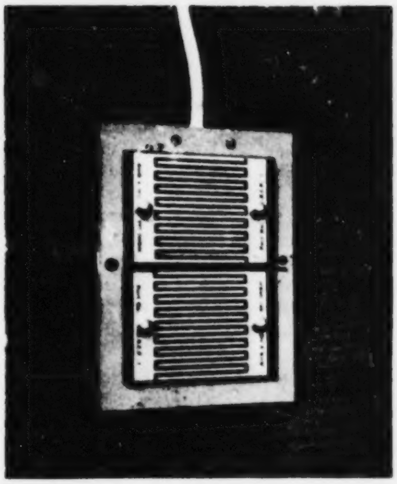


Figure 23 - Rain Detector for Automatic Precipitation Collector

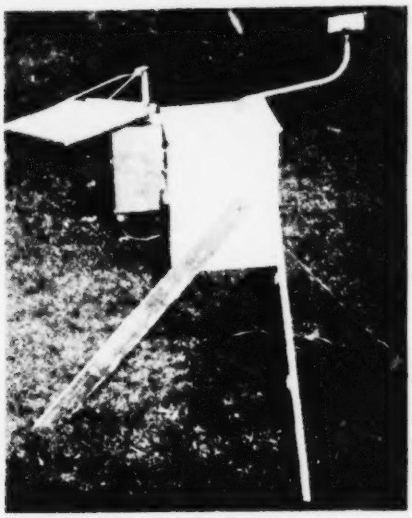


Figure 24 - Automatic Precipitation Collector (Open)

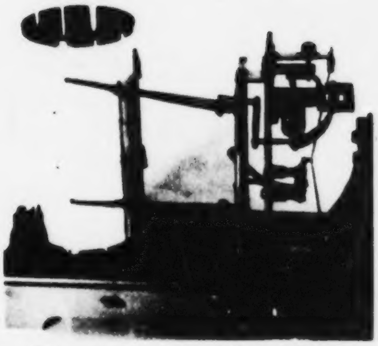


Figure 25 - Hygrothermograph

B Humidity

Because of its influence upon certain chemical reactions in the atmosphere and its influence upon visibility, it may be desirable to measure humidity in connection with an air pollution investigation. Also, some air pollutants affect receptors differently with different humidities, so measurement may be of importance in this respect.

1 Hygrothermograph

This instrument measures both temperature and humidity, activating pen arms to give a continuous record of each element upon a strip chart. The chart generally can be used for 7 days. The humidity sensor generally used is human hairs which lengthen as relative humidity increases and shorten with humidity decreases. Temperature measurements are usually made with a bourdon tube, a curved metal tube containing an organic liquid. The system changes curvature with changes in temperature, activating the pen arm. A hygrothermograph is shown in Figure 25.

2 Psychrometers

Humidity measurement by a psychrometer involves obtaining a dry bulb temperature and a wet bulb temperature from a matched set of thermometers. One thermometer bulb (wet bulb) is covered with a muslin wick moistened with distilled water. There must be enough air motion to cause cooling of the wet bulb due to evaporation of the water on the wick. A motor driven fan may be used to draw air at a steady rate past the moistened wick while a reading is taken. A sling psychrometer has both thermometers mounted on a frame which is whirled through the air to cause cooling by evaporation. Relative humidity is determined from the dry and wet bulb readings through the use of tables. Continuous measurements of humidity are not obtained using psychrometers.

C Radiation

The influence of the sun's radiation upon the turbulence of the atmosphere and upon certain photochemical reactions is sufficient to make measurements of radiation of importance. In addition, radiation may be reduced due to particulate pollution in the atmosphere. Particularly for research purposes, it may be desirable to measure this effect by comparisons between urban and non-urban stations similarly instrumented.

1 Total Radiation

The direct radiation from the sun plus the diffuse radiation from the sky may be measured by pyranometers. These instruments are mounted so that the sensor is horizontal and can receive the radiation throughout the hemisphere defined by the horizon. The instrument illustrated in Figure 26 is of this type.

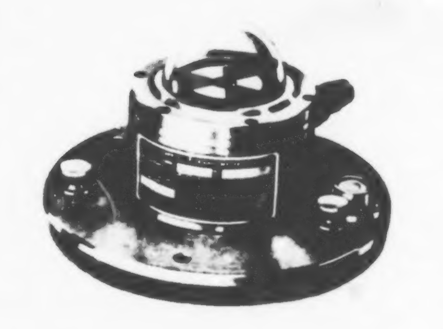


Figure 26 - "Black and White" Pyranometer

2 Direct Solar Radiation

Normal incidence pyrheliometer -

The direct solar radiation may be measured continuously by using the pyrheliometer shown in Figure 27 mounted upon an equatorial mount (Figure 28) to keep it pointed toward the sun. By using filters, different spectral regions of radiation may be determined.

3 Net Radiation

The difference between the total incoming (solar plus sky) radiation and the outgoing terrestial radiation may be

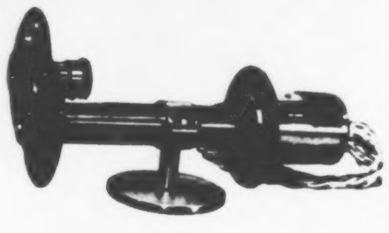


Figure 27 - Pyrheliometer

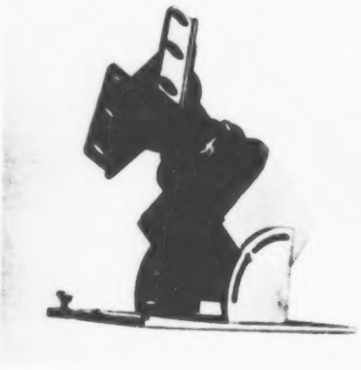


Figure 28 - Equatorial Mount

Figure 29 - Net Radiometer

useful in determining the stability, and hence, the turbulent character, of the lowest portion of the atmosphere. A net radiometer is shown in Figure 29.

D Visibility

Visibility, in addition to being affected by precipitation, is affected by humidity and air pollution. Frequently, visibility is estimated by human observer. An instrument to measure visibility, called a transmissometer, measures the transmission of light over a fixed baseline, usually on the order of 500 to 750 feet. An intense light source from the projector is focused on a photocell in the detector. The amount of light reaching the photocell over the constant baseline distance is assumed to be proportional to visibility. The transmissometer is restricted to estimating visibility in one direction only.

A transmissometer is also limited in that the light transmission it detects is affected mainly by liquid droplets in the air. It does not detect, to any great efficiency, the particulate matter in the atmosphere. The projector is shown in Figure 30 and the detector in Figure 31. A relatively new instrument, called a nephelometer, has been developed that will indicate visibility as it is affected by particulate matter in the atmosphere. An integrating nephelometer is shown in Figure 32.

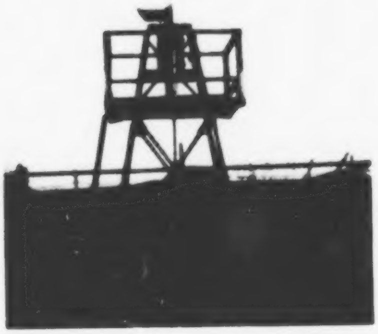


Figure 30 - Transmissometer Detector

Figure 31 - Transmissometer Receiver

Figure 32 - Integrating Nephelometer

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Exposure of Instruments

Ronald C. Hilfiker

EXPOSURE OF SURFACE INSTRUMENTS

INTRODUCTION

Exposure of instrumentation is undoubtedly one of the most important steps in any air pollution study. It is absolutely necessary to locate the instrumentation in such a manner that the measurements are representative of the area in which one is interested. In some cases, such as street level measurements in a city, it is desirable to obtain measurements of extremely local phenomena, but generally in air pollution meteorology, measurements that are representative of a fairly large area are desired. In this latter case, extreme care must be taken to ensure that the parameter being measured is not influenced by nearby obstacles.

An example of the effect of a building on regional wind flow is shown in Figure 1. Figure 1a shows two identical aerovanes mounted on a tower approximately 20 feet south of a 12 foot high building. The only difference in exposure between the two aerovanes is the 6 foot difference in height. It can be seen from Figure 1b that when the wind is blowing from the west, both sensors are apparently free of building influence, with both wind traces indicating typical mechanical type turbulence. However, when the wind shifts to the north-west, the turbulence characteristics change markedly in the wind flow being sensed by the Bendix aerovane at the 6 foot level. At the 12 foot level, the Belfort aerovane continues to indicate typical mechanical type turbulence. Which trace is indicative of the regional wind flow? It is the purpose of this chapter to explore the concepts needed to answer this question.

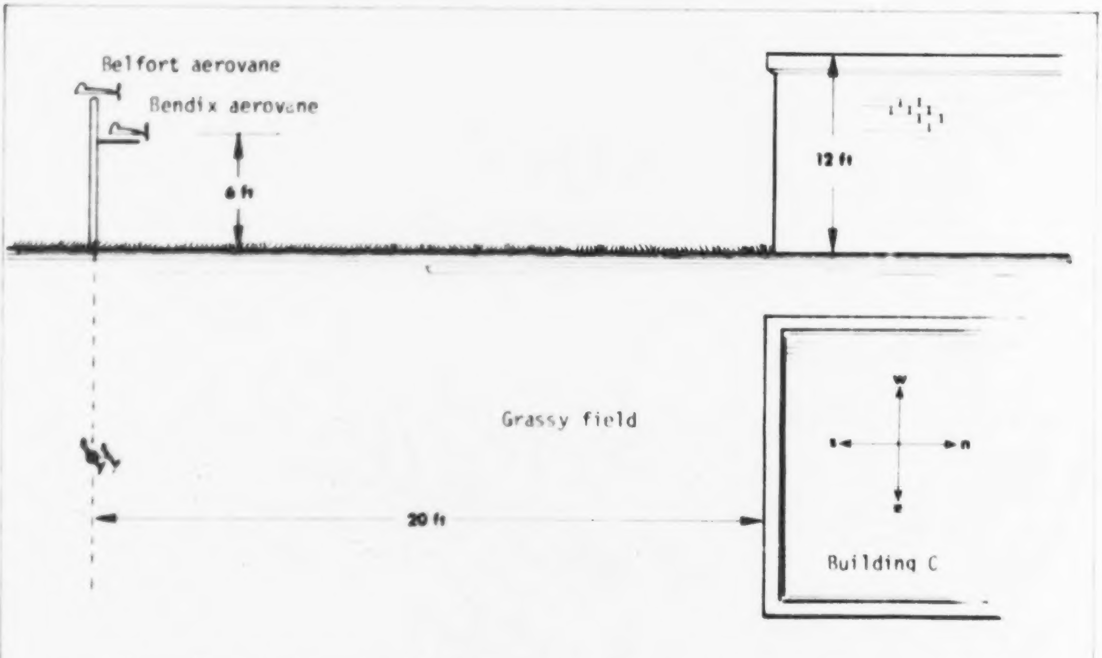

Figure 1a Location of wind equipment that produced the traces of figure 1b

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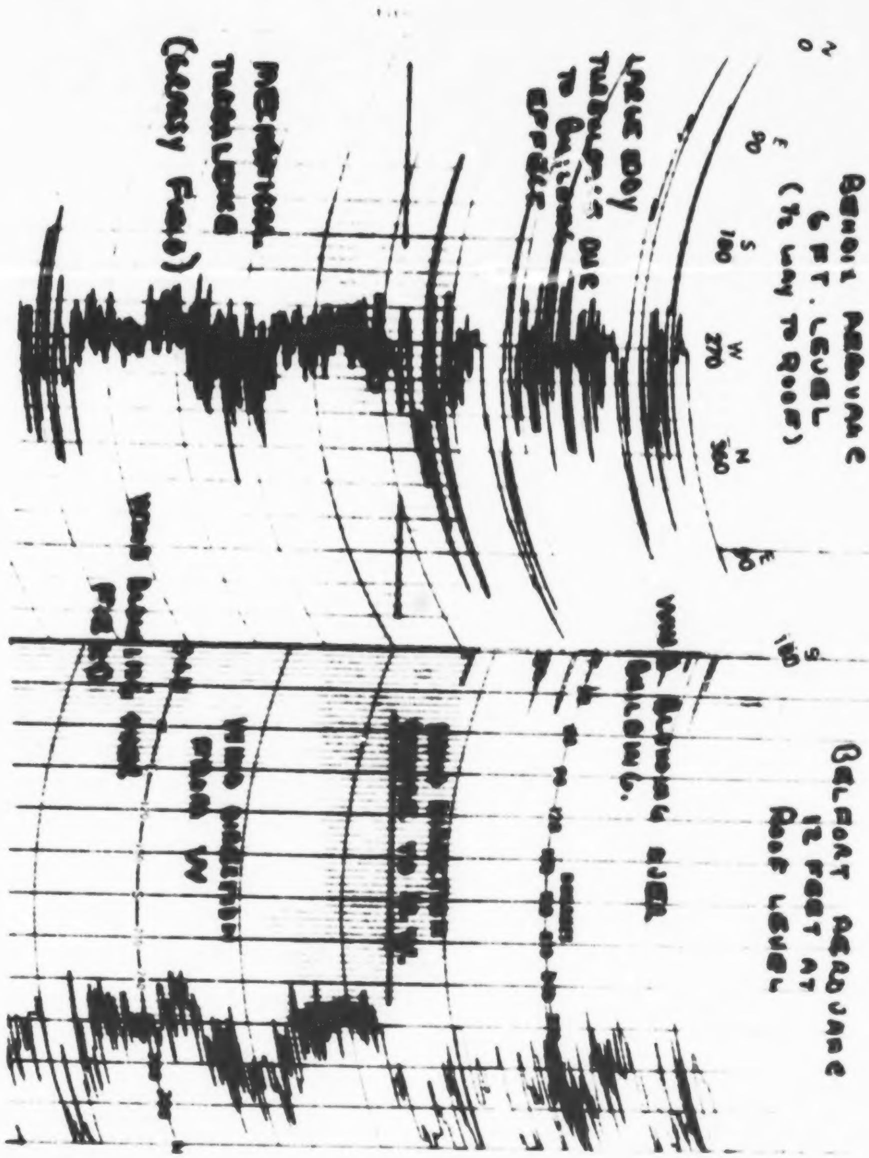

Figure 1b. Wind trace produced by the aerovanes of figure 1a

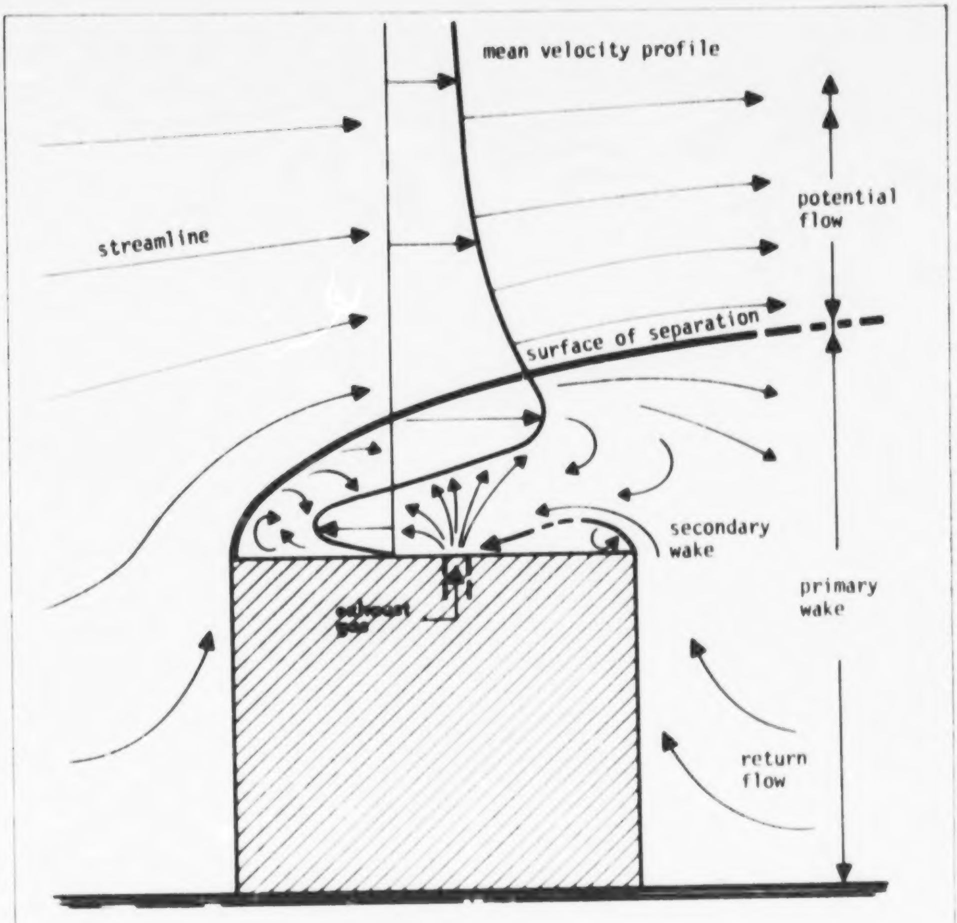
mean velocity profile
streamline
potential flow
surface of separation
secondary wake
primary wake
exhaust gas
return flow

Figure 2 Typical flow pattern around a cube with one face to the wind

ANEMOMETERS AND WIND VANES

In recent years, an attempt has been made at standardizing the height above ground at which "surface wind" measurements will be taken. The World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA) have agreed on 10 meters for this standard height. Ideally the measurements would be taken over level, open terrain, but very rarely do these conditions exist in an air pollution survey area. What rules of thumb or guidelines can be followed if obstructions are present in the vicinity of the spot where wind measurements are to be taken?

Figure 2 illustrates a typical flow pattern around a cube that has one face normal to the wind flow. From Figure 2 several things can be noted:

1) The flow is disturbed on the upwind and downwind sides of the obstruction.

2) The flow is disturbed above the building to a height of about 1 to 1 1/2 building heights above the roof.

3) Very near the roof of the building a reverse flow occurs.

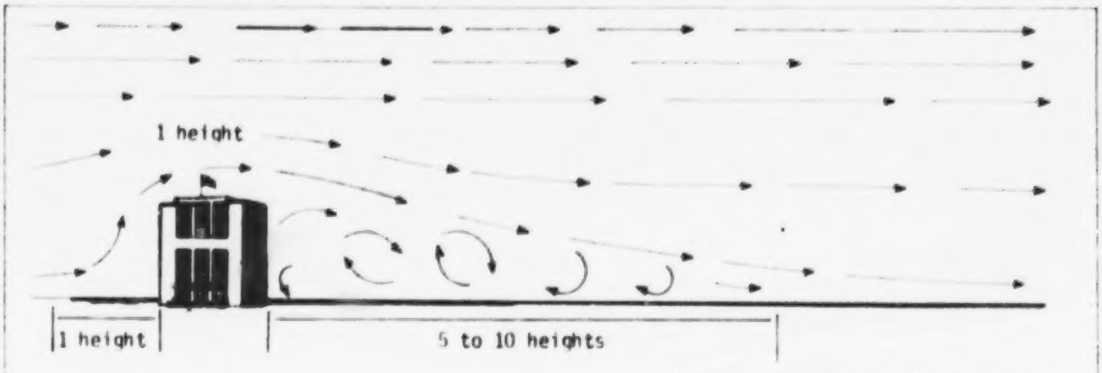

Figure 3 Building effect on wind

Figure 3 shows a more extensive view of the disruption in the ambient air flow around an obstruction. From Figure 3, one can formulate three rules of thumb for locating a wind system around an obstruction while keeping the sensor located in the ambient air flow:

1) The sensor must be located a distance upwind of the building equal to the building height.

2) If the sensor is to be located on the roof of the building it must be at least one building height above the roof.

3) The sensor must be located a distance of 5 to 10 building heights in the downwind direction.

These guidelines would apply most directly to a cubical obstruction standing by itself on open, level terrain. As the shape of the obstruction changes or as more obstructions become involved, the problem becomes much more complex. For example, suppose that it is desired to make measurements of the ambient air flow in the downtown area of a large city. Most probably the above guidelines could not be met because of the close proximity of the obstructions in a downtown area. A modification of these guidelines must be used. The sensor should be mounted on the roof of the tallest structure available, a distance above the roof determined by the proximity of taller buildings (using Guidelines 1 and 3), and the height of the building above the surrounding structures (utilizing Guideline 2). The exact height at which to locate the sensor would depend on the particular case.

In locating wind sensors in rough terrain or in valley situations, it will be necessary to determine if local effects such as channeling, slope and valley winds, etc., are of greatest importance, or whether flow above these influences is the parameter to be sensed. As in the urban situation, if the study centers upon elevated pollution sources, it may be desirable to avoid the local influences. However, if pollution from ground level sources is being emphasized, local influences may be of great importance. Remember that topographic influences such as hills, ridges, etc., produce flow patterns similar to those shown in Figures 2 and 3.

TEMPERATURE

As with wind sensors, thermometers are usually placed at a standard height above ground. This standard height has been set, by international agreement, at 1.25 to 2 meters (4-6.5 feet) above a grassy surface. Environmental considerations produce the following three rules of thumb for exposure of temperature sensors.

1) The sensor must be shielded from direct solar radiation.

2) The sensor must be well ventilated at a constant ventilation rate. (not less than 4-5 m/sec.)

3) The sensor must be uninfluenced by nearby features that might affect temperature.

If the sensor is of the thermocouple or thermister type, the aspirated shield of Figure 4 will fulfill the requirements of (1) and (2) above.

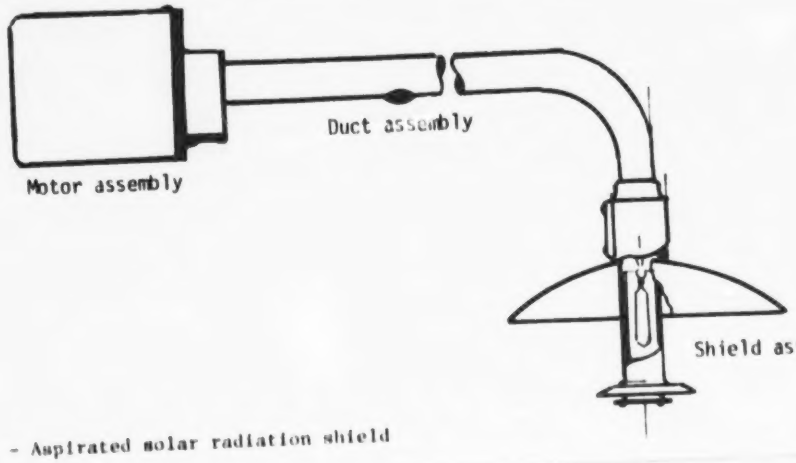
Duct assembly
Motor assembly
Shield assembly

Figure 4 - Aspirated solar radiation shield

If a standard thermometer is to be exposed, the cotton region shelter of Figure 5 will fulfill requirement (1) above. Ventilation will be natural and therefore variable in rate so the requirement of rule (2) is not met exactly, but for standard thermometers, the error or effect is negligible.

If the shelter of Figure 5 is to be used, care should be taken to orient the door towards the north to eliminate solar heating of the thermometers while taking a reading. The thermometers should also be located as close to the center of the shelter as possible.

Requirement (3) above ensures that ambient air temperature is being measured, and not the temperature of a micro-environment such as the air very near the south side of a brick building or near an asphalt roadway or parking lot.

RELATIVE HUMIDITY

Since relative humidity is not only a function of the amount of water vapor in the atmosphere, but is also dependent on temperature, exposure criteria outlined for temperature should also be observed for relative humidity.

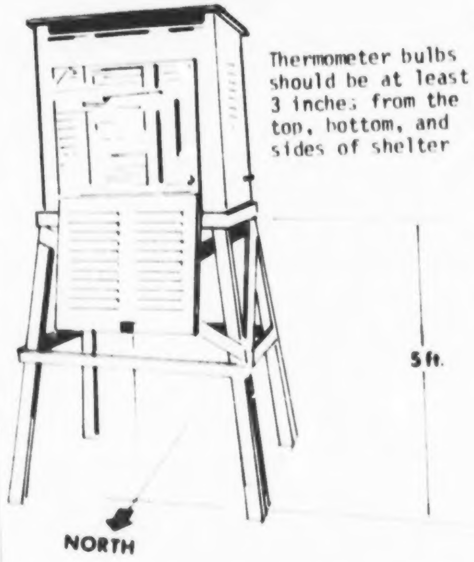
Thermometer bulbs should be at least 3 inches from the top, bottom, and sides of shelter
5 ft.
NORTH

Figure 5 - Cotton region type instrument shelter

PRECIPITATION

The previous section describes the design and operation principles of rain gauges. Care must be taken in the exposure of a rain gauge to ensure that the collection efficiency of the gauge is not reduced. Wind and its associated turbulence are the two most important factors that would tend to change the collection efficiency of the gauge. If the wind blows the rain into the gauge on a slant, the collection area is changed and therefore the efficiency would be changed producing an error in the indicated rainfall. If considerable turbulence exists around the gauge, the rainfall itself will be disturbed, again producing errors in the indicated rainfall. These considerations produce the following guidelines:

1) The gauge should be free of overhanging obstructions.

2) The gauge should be a sufficient distance from obstacles to avoid local eddys.

3) The gauge should be sheltered from the possiblity of high wind speeds at the gauge.

Ideally, all three criteria could be met if the gauge was located in a clearing in a woods or orchard where the diameter of the clearing is about equal to the height of the surrounding trees. A windshield, such as the one shown in Figure 6, can also be installed to reduce the distortion of the air flow around the gauge.

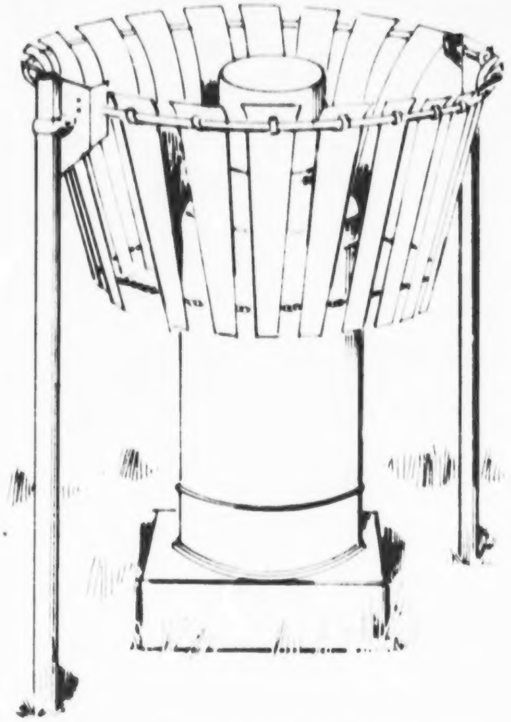

Figure 6 - Shielded rain gauge

RADIATION

Solar radiation measurements require exposure that will insure no obstructions between the sun and the sensor during any part of the year, and in the case of total solar radiation (direct and diffuse) as clear a view as possible of the entire sky is necessary.

The measurement of net radiation requires that the sensor be placed far enough away from the earth's surface to receive terrestial radiation over a representative area, yet not far enough from the surface to receive radiation from a thick air layer above the surface. For net radiation measurements, a height between 1 and 2 meters (3 to 6 feet) is generally recommended.

EXPOSURE OF INSTRUMENTS ON TOWERS OR STACKS

INTRODUCTION

In striving to meet the exposure criteria outlined in the last section, it is often necessary to mount meteorological sensors on towers or masts. Unless these sensors are mounted properly, errors will be introduced in the measurements due to the influence of the tower on the parameter being sensed. It is the purpose of this section to set forth guidelines to eliminate these tower induced errors.

WIND SYSTEMS

If a wind system (anemometer and vane) are to be mounted on top of a tower, little concern is needed as to exposure. If, however, wind equipment is to be installed on the side of the tower, precautions should be taken to ensure that the wind measurements are not influenced by the tower. An analysis by Gill and Olsson (1967) has shown that the turbulence in the wake of lattice-type towers is moderate to severe, and that in the wake of solid towers and stacks is extreme, often with reversal of flow.

Another study by Moses and Daubek (1961) revealed that the air flow on the lee side of a tower may be reduced to about one-half its true value under light wind conditions and about 25% for higher winds (10-14 mph). The study also revealed that when the wind blowing toward the anemometer made an angle of 20 to 40° with respect to the sides of the tower adjacent to the anemometer, the measured wind speed exceeded the true wind speed by about 30%.

These studies illustrate the necessity of proper exposure.

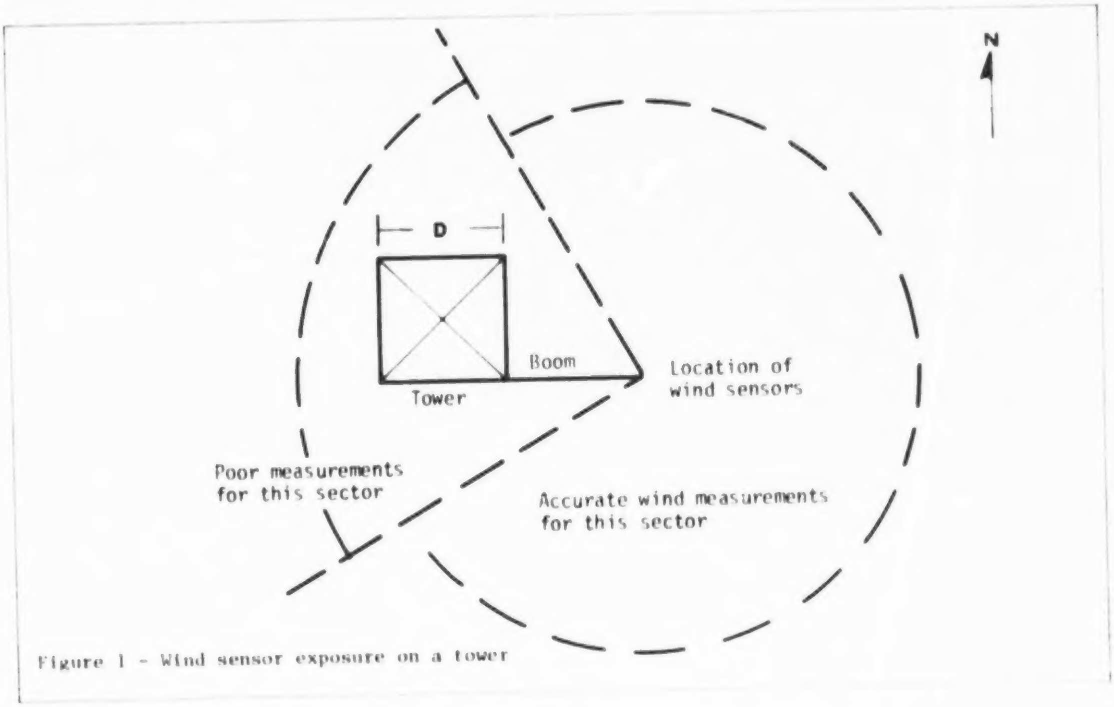
N
D
Boom
Tower
Location of wind sensors
Poor measurements for this sector
Accurate wind measurements for this sector

Figure 1 - Wind sensor exposure on a tower

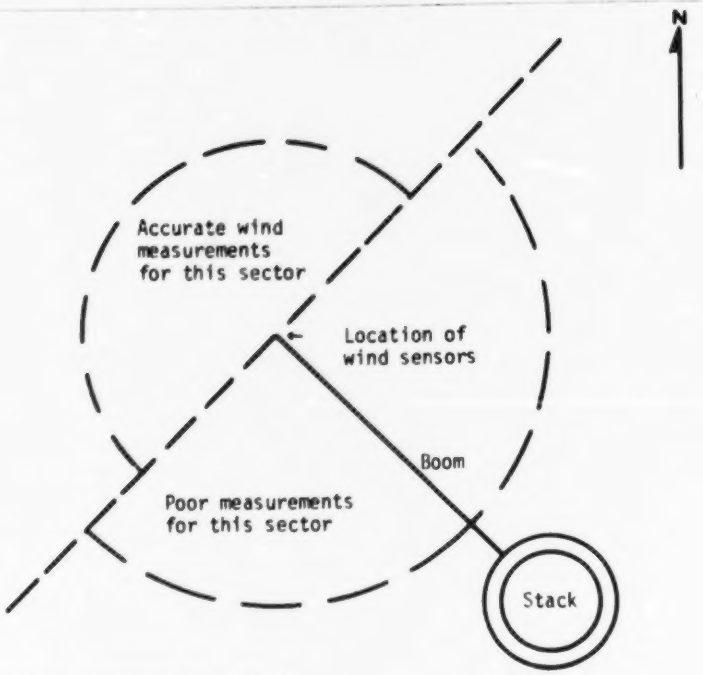
N
Accurate wind measurements for this sector
Location of wind sensors
Boom
Poor measurements for this sector
Stack

Figure 2 - Wind sensor exposure on a stack

Figure 1 illustrates the correct exposure of a wind sensor on an open tower. The following exposure criteria should be observed:

1) The boom should extend outward from a corner of the tower into the wind direction of primary concern.

2) The boom should place the sensor out from the tower a distance not less than the length of a side of the tower. (length D in Figure 1)

3) The wind sensors should be located at heights of minimum tower density, and above or below horizontal cross members.

If the above guidelines are followed, the following accuracies can be expected:

1) For a boom length of 1D, measurements of wind speed are true within ± 10% for a 310° sector of arc.

2) For a boom length of 2D the wind speed is accurate within ± 10% for a 330° sector of arc.

3) For these two arcs, wind direction is accurate to within approximately ± 5%.

With a boom length of 1 -2D, wind speed and direction measurements within ± 5% can only be obtained for a 240 - 270° sector of arc. This is the case illustrated in Figure 1.

It has been found in practice that the maximum practical boom length is about 20-30 feet. If the wind sensors are to be mounted on very large towers (TV towers or fire look-out towers), the sector of arc yielding accurate wind measurements may drop to 180° due to the fact that the boom length may be less than 1D.

In any case, if accurate wind measurements are required for an arc sector greater than that produced by the above exposure criteria, it is recommended that two sets of speed and direction sensors be placed at 180° apart in the manner prescribed in the above guidelines.

EXPOSURE OF WIND SENSORS ON CLOSED TOWERS OR STACKS

Preferably, closed towers or stacks should not be used to support meteorological sensors. If a stack must be used, the following exposure guidelines should be observed:

1) The boom should place the sensor out from the stack a distance not less than 2 stack diameters.

2) Instruments should never be located within 2-5 stack diameters of the top of an active stack.

Figure 2 illustrates the correct exposure of a wind sensor on a stack. If the above guidelines are used one can expect accurate wind measurements (± 5 to 10% of true value) through an arc of only 180° as shown in Figure 2. As with towers, if accurate wind measurements through a full 360° of Azimuth are desired, it is recommended that two sets of wind systems be used. These two systems should be located 180° apart, and exposed according to the above guidelines.

TEMPERATURE SYSTEMS

Temperature sensors should also be exposed on booms out from the tower structure to assure that the temperature of the air sampled is not influenced by thermal radiation from the tower itself. Temperature sensors should never be mounted on stacks.

Booms for temperature sensors need not be as long as for wind sensors, but generally, both wind and temperature sensors are located on the same boom at about the same distance from the tower. The temperature sensors themselves must be shielded and ventilated as described in the previous section.

SPACING OF WIND AND TEMPERATURE SYSTEMS

Figure 3 illustrates a typical spacing of wind and temperature systems on a tower. Wind sensors are normally spaced at logarithmic height intervals (10,20,40,80, 160 meters) because of the normally logarithmic change of wind speed with height.

Temperature measurements should be made at close intervals near the ground, and at approximately equal intervals at greater heights as shown in Figure 3. A logarithmic spacing is not necessary since temperature profiles become approximately linear a short distance from the surface.

With both wind and temperature, provisions must be made for swinging or telescoping the boom in order to service the sensors. Provisions also must be made for orienting the wind vane correctly when the boom is in the service position.

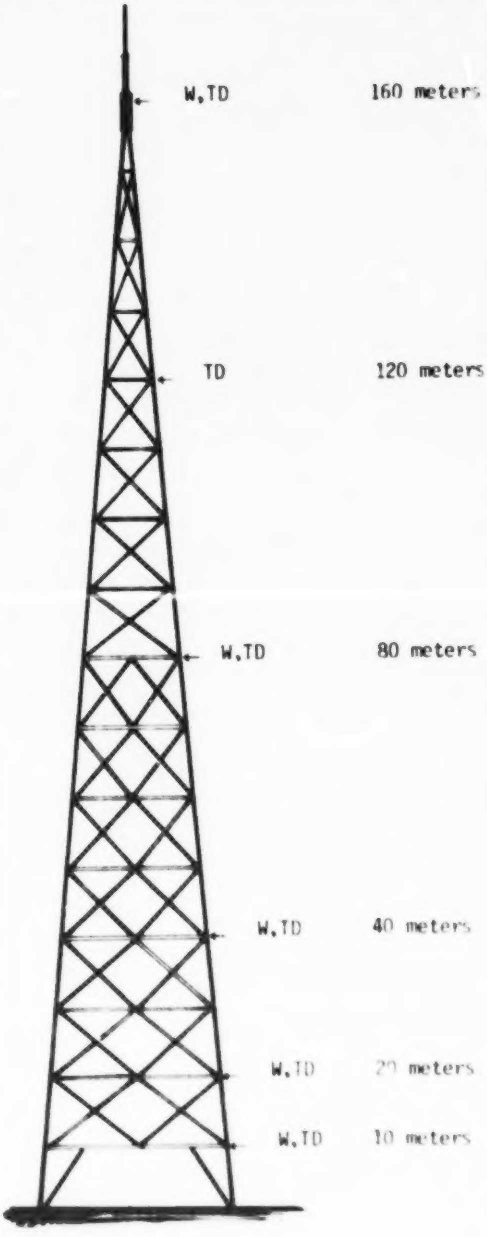

Figure 3 - Vertical spacing on a tower

EXPOSURE OF AIRBORNE INSTRUMENTS

INTRODUCTION

The measurement of meteorological parameters aloft may require the use of such devices as balloons, aircraft, rockets, etc. With many of these methods, surface-based receiving and recording instrumentation is necessitated. Therefore, a discussion of the exposure of airborne instruments must also include a discussion of the exposure of the surface-based support equipment.

EXPOSURE OF SURFACE BASED SYSTEMS

The measurement of wind aloft by balloon tracking may involve the use of radar or radio direction-finding equipment. Sites for radio and radar equipment should be on relatively high ground with the horizon as free from obstructions as possible. Of greatest importance to free balloon launchings is that there be no nearby obstructions to hinder the flight of the balloon. The operation of captive balloons (wiresondes) should be carried out only in open areas and never near power lines. Particular care should be taken to properly ground all captive balloon equipment and operations should be carried out only during periods of minimal atmospheric electrical potential. It should be noted that FAA authorization is necessary for most captive balloon operations.

EXPOSURE OF AIRCRAFT MOUNTED SYSTEMS

The main exposure problem associated with measurements from an aircraft is the fact that the sensors must be exposed to undisturbed air. Fixed wing propellor slipstreams and helicopter downwash must be avoided. For temperature measurements, engine and cabin heat must also be avoided, and a correction must be made for airspeed. Vibration of receiving and recording instrumentation in the aircraft may also be a problem.

The following guidelines are suggested for exposure of aircraft mounted sensors:

1) On fixed wing aircraft, sensors are most effectively mounted on the wingtips, forward of the wing not less than two feet.

2) On a helicopter, sensors are most effectively mounted on the forward tip of one of the skids, provided a forward speed of about 15 m/sec is maintained. This forward speed would project the downwash behind the sensor.

3) To reduce recorder vibrations, mountings of sponge rubber or plastic should be used.

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Exposure of Meteorological Instruments

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2) Moses, H., and Daubek, H.G., "Errors in Wind Measurements Associated with Tower-mounted Anemometers", Bulletin of the A.M.S., Vol. 42, No. 3, 1961 pp 190-194

SECTION SEVEN

FURTHER APPLICATIONS OF METEOROLOGY TO AIR POLLUTION

Air Pollution Weather Forecasts
Air Pollution Surveys
Site Selection for a Pollutant Source
Atmospheric Tracers and Urban Diffusion Experiments
Meteorological Models for Urban Areas
Sources of Meteorological Data

AIR POLLUTION WEATHER FORECASTS

J.R. Zimmerman*

A program to provide air pollution weather forecasts has been in effect on a year-round basis since August 1960, for the eastern U.S. and since October 1963, for the contiguous 48 states. The purpose of the program is to forecast meteorological conditions which are favorable for the accumulation of contaminants in the atmosphere. These forecasts are disseminated to public and private interests by the National Weather Service, NOAA.

I DEFINITION

A high potential for community air pollution has been defined as a set of weather conditions conducive to the accumulation of atmospheric pollutants over 36 hours or more and over an area of about 58,000 nautical mi^2 (76,000 statute mi^2) or more. Niemeyer,(6) Boettger,(1) and others have found that such conditions (e.g., hourly surface wind speeds generally not exceeding 7 kt., winds aloft not exceeding 25 kt., and subsidence below 600 mb) occur when high pressure exists at the surface and there is a warm-core ridge aloft. This is the basic synoptic weather situation that the air pollution forecaster attempts to anticipate. The warm core ridge aloft is extremely important since it is indicative of a slow-moving surface pressure system. If the surface anticyclone becomes quasi-stationary, as it often does in such situations, perturbations aloft and at the surface are forced to move around the system. While poor dispersion also occurs during other types of weather situations, the warm-core anticyclone is considered the "text book" model of stagnation.

II BACKGROUND

ESSA meteorologists assigned to the U.S. Public Health Service began issuing routine, operational forecasts of high air pollution potential for the area east of 105°W longitude in August, 1960. During the first year of this operation, 12 cases of air pollution potential occurred, of these, 10 were forecast (Miller and Niemeyer).(4)

In a climatological study of air pollution potential for the western United States, Holzworth,(3) also found that the large-scale synoptic feature most conducive to poor air quality was the quasi-stationary anticyclone. This study and the initial success of the forecast program for the eastern United States provided the background for a research program to extend the forecast area to include the western United States. An experimental forecasting program for the western United States was started in September 1961. The program was successful and on October 1, 1963 the operational forecast area for air pollution potential advisories was expanded to include all of the contiguous United States.

An isoline analysis of the total number of high air pollution potential (stagnation advisory) days forecast from the start of the program through April 3, 1970 is given in Figure 1. The area in the eastern half of the United States with the maximum number of air pollution potential days is located along the Appalachian Mountains. The respective area for the western United States is found over central California.

The initial success of the forecasting program (prior to 1962) was due mainly to the individual forecaster's judgement based on experience. While the necessity for some forecasting judgement has always been required, especially when fixing the boundaries of high air pollution potential areas, it was recognized that the consistency and reliability of the forecasts could be improved by employing objective forecasting aids. Such an aid was developed for the eastern United States by V.D. Urban (unpublished) and for the western United States by Miller.(4)

Since these forecasting methods have been developed, many additional refinements have

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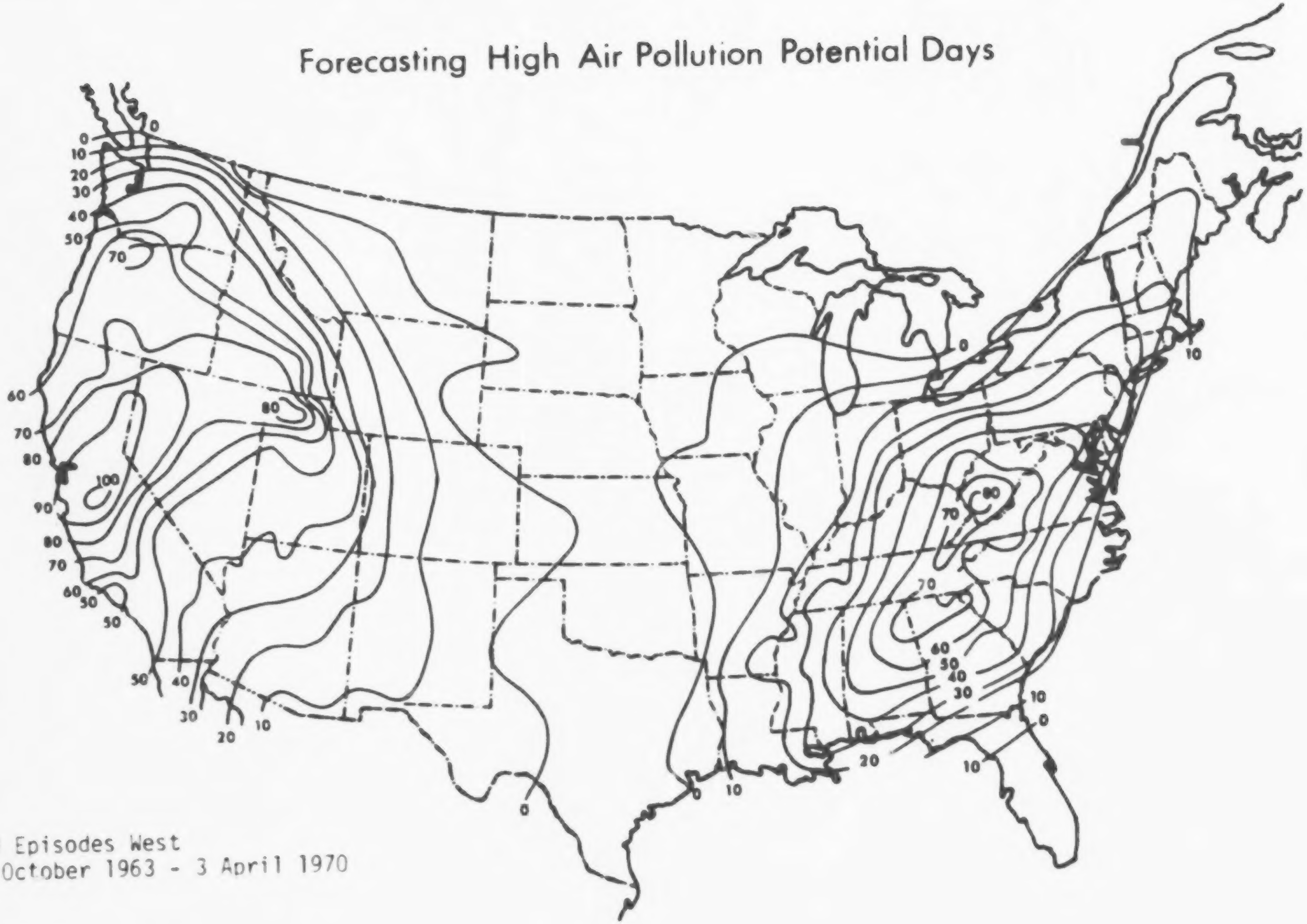
Forecasting High Air Pollution Potential Days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39 Episodes West
1 October 1963 - 3 April 1970

75 Episodes East
1 August 1960 - 3 April 1970

Figure 1.

been introduced. The forecast program is by no means in its ultimate form, as continuing research is directed toward the development of more useful forecasts and more accurate forecasting techniques.

Under the present system (as of March, 1967) the primary meteorological parameters considered pertinent to large scale dispersion are:

1. The mixing layer depth, L.
2. The mean wind speed through the mixing layer or transport wind speed, u.

Forecasting these two parameters, therefore, is basic to the air pollution potential forecasting program.

III MIXING LAYER CALCULATIONS

A Today

In order to evaluate the dispersion conditions for today, the day is divided into two time periods representing approximately the usual diurnal times of maximum and minimum dispersion, these time intervals are referred to as "afternoon" and "morning", respectively.

The calculations made are:

1. Morning urban mixing depth (MNDP)
2. Average transport wind speed through the morning mixing depth (AWS12)
3. Afternoon mixing depth (MXDP)
4. Average transport wind speed through the afternoon mixing depth (AWS00).

At night as the atmosphere traverses an urban area, it usually acquires a significant amount of heat from urban sources, causing the temperature of the air over the city to be somewhat warmer than that upwind of the city. This phenomenon is called the urban "heat island".(2) An important effect of the urban heat island is to establish a lapse rate over the city that is usually more unstable than the lapse rate over the rural area upwind of the city. The net result is a mixing layer over the city at night that may be as high as several hundred meters.

To simulate this effect, 5°C is added to the minimum temperature during the night. Then the height is determined where the dry adiabatic lapse rate from this surface temperature intersects the temperature - height profile observed (by rawinsonde) at 1200 GMT. This height is called the morning urban mixing depth (MNDP) and represents a rough value of mixing depth during the morning period over an urban area (See Figure 2).

To determine the greatest depth of the mixing layer (MXDP) that is expected during the day and the same procedure is repeated using the forecast maximum surface temperature.

The average wind speed through the mixing layer for the morning (AWS12) and afternoon (AWS00) periods is calculated by taking the arithmetic average through the mixing layer of the wind speeds aloft. For the morning period the speeds observed at 1200 GMT are used, but for the afternoon period forecast speeds are used.

B. Forecast for Tomorrow

The next phase of the forecast procedure is to determine the most probable values of mixing depth and mixing layer wind speeds which will occur tomorrow. An objective method of forecasting the mixing depth for tomorrow morning has not been developed. With experience, however, one-day changes in the morning urban mixing depth are readily anticipated from the prognostic synoptic situation. In addition during high air pollution potential conditions, morning urban mixing depth criteria are almost always met. To forecast tomorrow afternoon's mixing depth the method developed by Miller(7) is used. This technique makes use of regression relationships between forecast parameters and the mixing depth and mixing layer

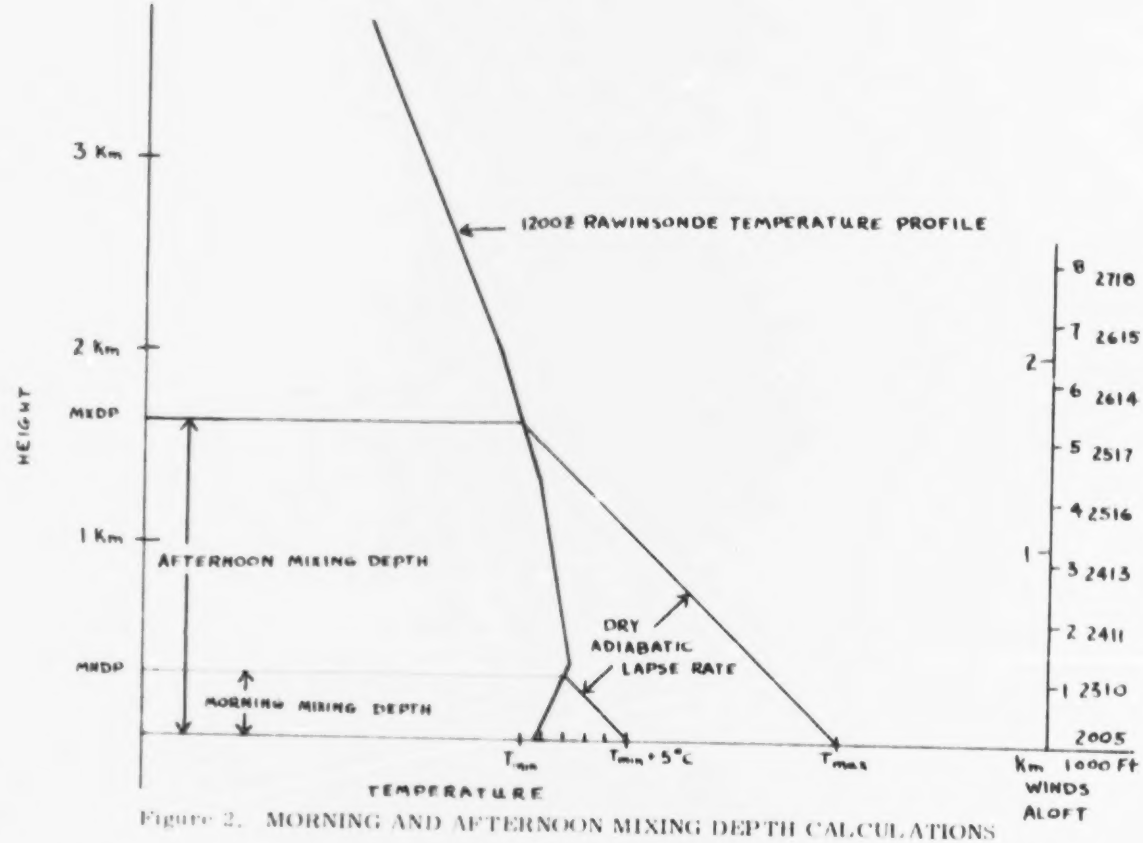

3 Km
2 Km
MXDP
1 Km
MNDP
HEIGHT
1200Z RAWINSONDE TEMPERATURE PROFILE
AFTERNOON MIXING DEPTH
MORNING MIXING DEPTH
DRY ADIABATIC LAPSE RATE
T_{min}
T_{min} + 5°C
T_{max}
TEMPERATURE
8 2718
7 2615
2
6 2614
5 2517
4 2516
1
3 2413
2 2411
1 2310
2005
Km 1000 Ft
WINDS ALOFT

Figure 2. MORNING AND AFTERNOON MIXING DEPTH CALCULATIONS

transport wind speed, equations have been determined for each rawinsonde station.

To forecast tomorrow's afternoon mixing depth, the forecast parameter used is:

$$\Delta T = T_{max} - T_v \qquad (3)$$

where T_{max} = the maximum surface temperature forecast for tomorrow

T_v = the mean virtual temperature of the standard layer in which the top of the mixing layer lies.

The mean virtual temperature is calculated for two standard layers:

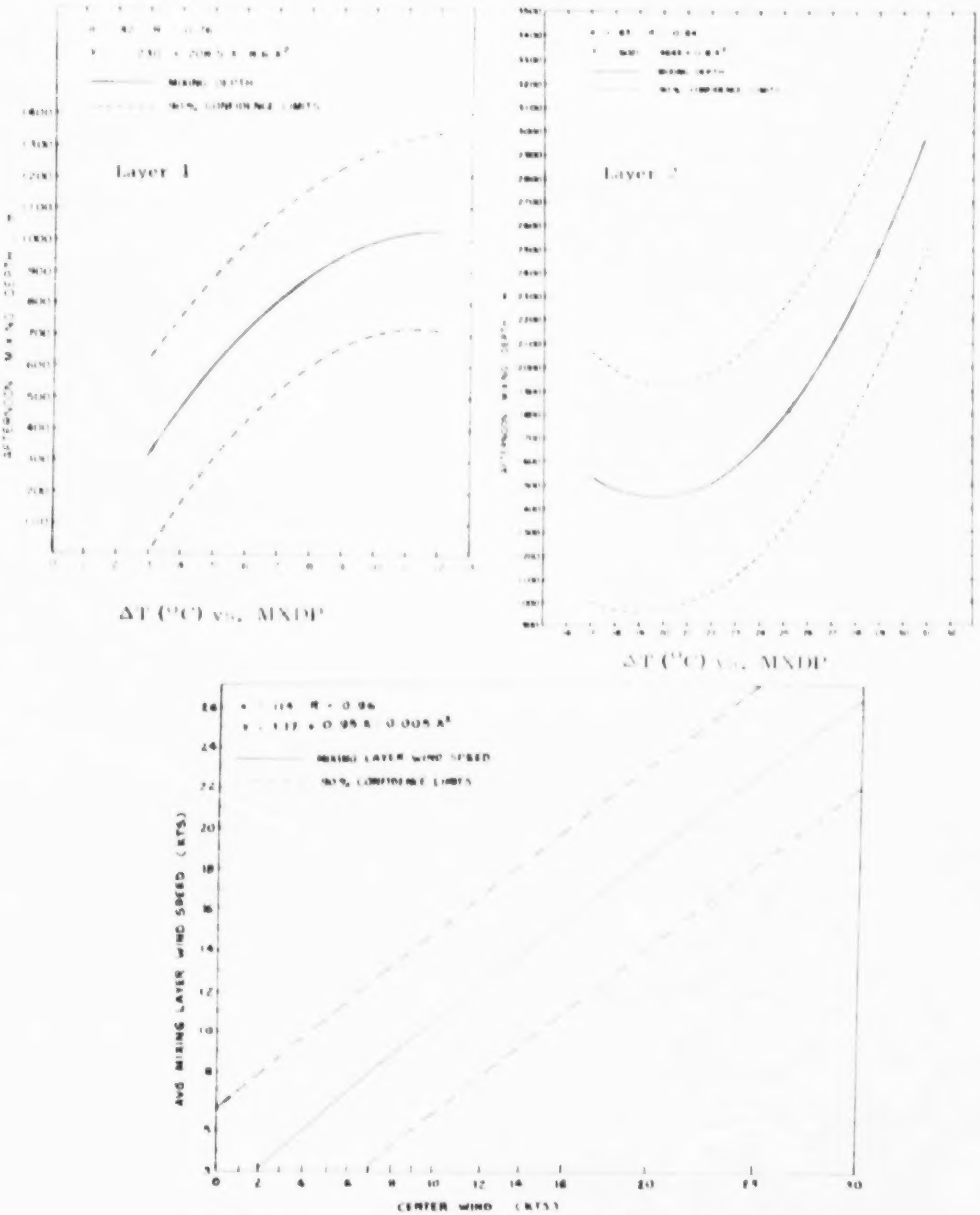
Layer 1 = 1000 to 850 mb (approximately 100 to 1,500 m)

Layer 2 = 850 to 500 mb (approximately 1,500 to 5,600 m)

That layer is used in which the top of the mixing layer is forecast to occur.

The forecast of the transport wind speed follows a similar technique with the use of regression relationships between the wind speed at the center height of the mixing layer and average wind speed through the mixing depth. After the mixing depth has been determined, the forecast wind speed at the center height of the mixing depth is obtained from routine

Weather Bureau forecasts. Then individual regression relationships for each rawinsonde station determine the forecast mixing layer wind speed. The regression relationships for Dayton, Ohio are shown in Figure 3.



ΔT (°C) vs. MXDP

ΔT (°C) vs. MXDP

Figure 3. REGRESSION CURVES OF MIXING DEPTH AND MIXING LAYER WIND SPEED

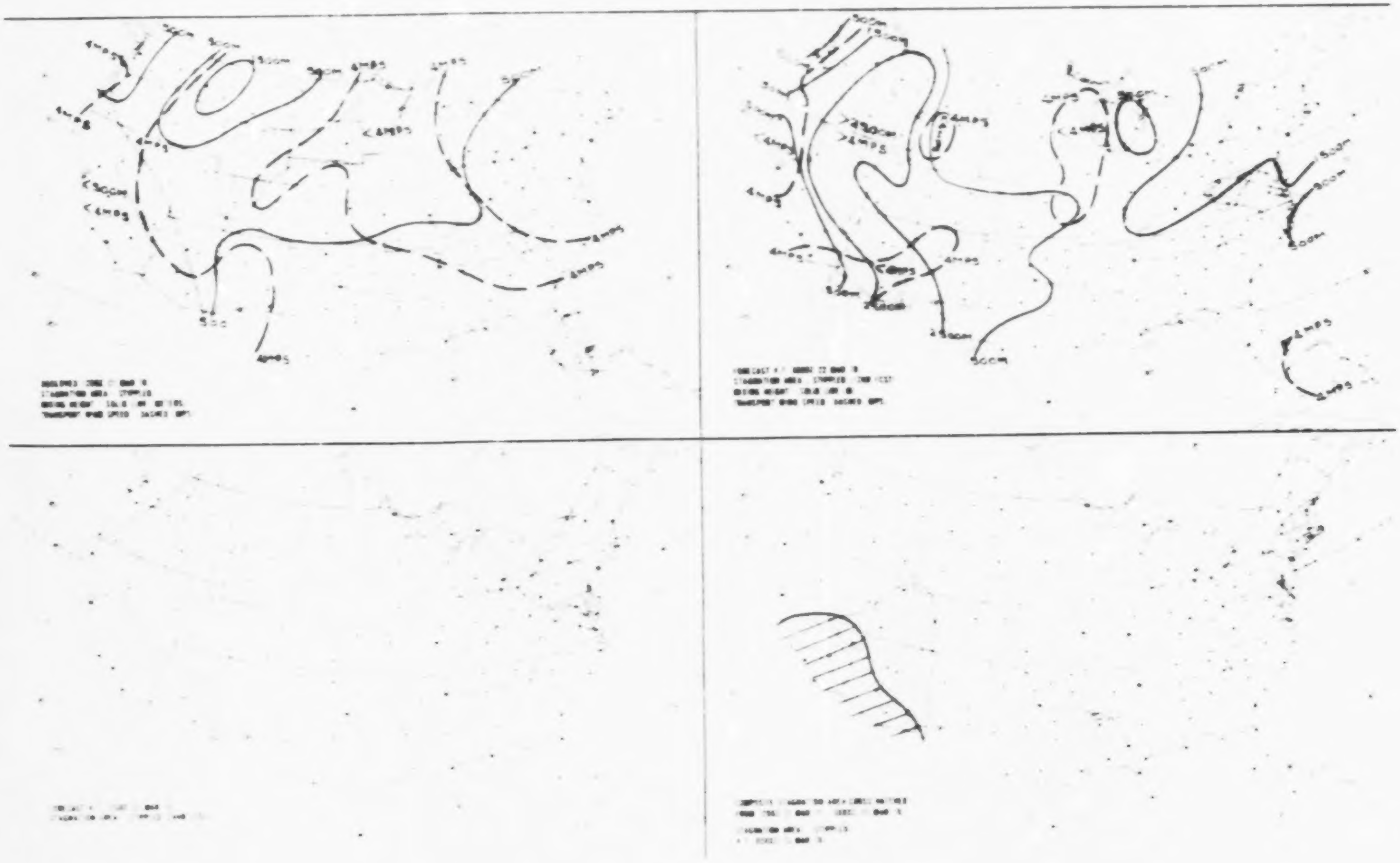

500m
4mps
<4mps
<500m
>2400m
>4mps

Figure 3. Sample Facsimile Transmission

Further details concerning this forecast scheme can be found in the original publication.(7)

All of the mixing layer calculations which have been described are made automatically by high-speed computers at the National Meteorological Center at Suitland, Md. for each of the 70 Weather Bureau rawinsonde stations. These data are then evaluated to determine synoptic scale areas where poor dispersion exists and is expected to persist for at least 36 hours. The criteria used to determine the areas of high air pollution potential are:

1. Morning urban mixing depth (MMDP) ≤ 500 m
2. Morning transport wind speed (AWS 00) ≤ 4.0 m/sec
3. Afternoon ventilation (MXDP X AWS 00) ≤ 6000 m^2/sec
4. Afternoon transport wind speed (AWS 00) ≤ 4.0 m/sec

IV. ADDITIONAL CRITERIA

Besides the mixing layer parameters, other elements considered when making an air pollution weather forecast are: precipitation in the forecast area, vorticity and vorticity changes, size, and persistence of the forecast area.

A. Precipitation is an important mechanism by which contaminants can be removed from the atmosphere.(8) In addition, precipitation is often accompanied by rapid dilution and sudden air mass changes. Therefore, one of the forecast criteria is that precipitation is unlikely to occur in the forecast area.

B. Vorticity and its change with time are associated with significant dynamic processes in the atmosphere. Small values of vorticity typically are associated with slow-moving anti-cyclones. Large values of vorticity indicate that the atmosphere is undergoing considerable change and that weather conditions are unsettled.

C. The size of a high pollution potential area forecast to persist for 36 hours or more must be equivalent to or larger than a longitude-latitude square of 4 degrees on each side.

D. Representative surface wind speeds as reported on hourly teletype sequences should be light; at each station no more than 3 of the 24 hourly observations in each day should exceed 8 kts. In many locations such as in uneven terrain, however, surface wind speeds may be high as a result of local conditions, (e.g., mountain-valley breeze). In these cases high wind speeds are not considered to be representative of the synoptic scale weather pattern and the surface wind speed criterion cannot be applied.

At present the program attempts to forecast only large areas of persistent meteorological conditions conductive to the accumulation of air pollutants; i.e., conditions that occur on a synoptic scale. It should be recognized that a city may experience heavy air pollution for periods of time less than 36 hours without a forecast of high air pollution potential being issued. Also, it is possible that a city may experience heavy air pollution for periods longer than 36 hours without a forecast being issued. The latter can occur if limited dispersion persists for more than 36 hours, but the affected area does not meet minimum size requirements.

CURRENT OPERATIONS

As of September 1, 1971, the terms "air pollution potential", "air pollution potential advisory", and "air pollution potential statement", together with the [illegible] of National Air Pollution Potential Advisories by NMC were discontinued. The following guidance products are currently transmitted from NMC:

1. Air Stagnation Index Forecasts - twice daily on FOFAX. These four panels depict areas of atmospheric stagnation, both observed and forecast, as shown in Figure 4, transmitted at 1008 and 2205 GMT.
2. Air Stagnation Data (FKUS 1) - once daily on teletype Service C.

based on 1200 GMT rawinsonde and low-level sounding stations in the U.S., calculated and forecast mixing heights and transport wind speeds are transmitted.

3. Air Stagnation Narrative (FKUS 2) - twice daily on Service C. These are plain language narratives at 1052 and 2327 GMT, describing the general synoptic situation as it applies to (1) above.

NOAA program elements responsible for issuing Atmospheric Stagnation Advisories (ASA) for specific geographical areas include Environmental Meteorological Support Units (EMSU), and accredited forecasters at selected Weather Service Forecast Offices (WSFO). Chapter C-30 of the NOAA NWS Operators Manual contains further details regarding the air pollution weather forecast program (1971).

The EPA requires that emergency action plans, prepared by state air pollution control authorities as a part of their implementation plan, contain, as a criteria to trigger preplanned episode reduction schemes, definite procedures for receiving an ASA, or equivalent report stating that a condition of atmospheric stagnation will exist for the next 36 hours. Additional information is contained in the "Guide for Air Pollution Episode Avoidance" (1971) and two related publications (1971).

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AIR POLLUTION SURVEYS

P. A. Humphrey[1]
J. A. Tikvart[1]

I DEFINITION AND PURPOSE OF AIR POLLUTION SURVEYS

A An air pollution survey is a critical examination of a given geographical area for the purpose of determining the nature, sources, extent, and effects of air pollution and their interrelationships. This includes:

1 Evaluating the character and magnitude of existing problems.

2 Estimating the potential for future problems or for the deterioration of a present problem.

3 Obtaining knowledge and understanding for the development of abatement and control measures.

B Brief inspections by enforcement officials and evaluations of combustion equipment or air and gas cleaning equipment do not qualify as surveys.

II TYPE AND SCOPE OF SURVEYS

A Local Source Problems (Determination of the extent to which a source affects the local ecology).

1 Large source with voluminous emissions.

2 Small source with emissions especially noxious or detrimental to the surrounding area.

B Site Selection Surveys

1 Sites for the construction of new industry.

2 Community planning and zoning

a Impact of a proposed plant or group of plants.

b Industrial park location.

C Area Surveys. Table 1 lists selected surveys not included in Tables 1 and 2 of Rossano (1962).

1 Appraisals involving little or no air sampling using available data.

a Determine current status of air pollution.

b Estimate future potential.

c Offer recommendations for prevention or abatement.

2 Small-scale intensive investigations (Sampling at one or more locations for a period of one to several weeks).

a Provides order-of-magnitude figures of levels and fluctuations of pollutant concentrations.

b Focuses attention of community on its growing problem and may provide opportunity for training.

3 Community air pollution surveys (Large-scale study involving considerable field and laboratory activities over a period of one or more years).

D Research Studies

1 Especially designed studies of an experimental nature.

a Meteorological transport and diffusion.

b Abatement procedures and control devices.

2 Post air pollution episode investigations.

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III THE COMMUNITY AIR POLLUTION SURVEY

- A Planning and Development
  - 1 State the problem
    - a Human health, animal and/or vegetation effects, materials deterioration
    - b Pollutants responsible
    - c Meteorology and topography effects on transport
  - 2 Define the depth of the survey
    - a Geographic area
    - b Money and personnel
      - 1) "paper" study - one man and secretary
      - 2) pollutant sampling and analyses program - interdisciplinary professional staff
    - c Time - short period or long term.
- B Operations
  - 1 Air pollutant source measurements (Emission inventory)
    - a Paper estimate
    - b Questionnaire and/or plant visit
    - c Source sampling
  - 2 Meteorological and topographic studies
    - a Climatology
    - b Tracer experiments
    - c Mathematical diffusion model
  - 3 Air sampling and analysis
    - a Time considerations in sampling
    - b Geographical (or geometrical) considerations
      - 1) Wind trajectories
      - 2) Concentric circles
      - 3) Network
      - 4) Mobile stations
      - 5) Three-dimensional measurements
    - c Design of aerometric stations
  - 4 Measurement of effects
    - a Biologic
      - 1) Impairment of health
      - 2) Odor nuisance
      - 3) Reduction of solar radiation and visibility
      - 4) Eye irritation
    - b Economic
      - 1) Corrosion of metals
      - 2) Deterioration of fabrics
      - 3) Damage to paint
      - 4) Soiling
      - 5) Reduction of solar radiation and visibility
  - 5 Photographic studies
    - a Ordinary ground and aerial photography
    - b Time lapse photography
    - c New photographic techniques
  - 6 Analysis of data
  - 7 Public relations and information
- C Evaluation and Report
  - 1 Interpretation
  - 2 Evaluation and Report, pro and con
  - 3 Presentation of concise, attractive and easily understood report.

Table 1. Selected List of Air Pollution Appraisals and Investigations of Limited Scope

DESIGNATION	DATE	RESPONSIBLE ORGANIZATION	SCOPE
Air Pollution in Maricopa County (Winter 1959-60)	1960	Maricopa County Health Dept. Division of Environmental Health Sanitation Bureau of Public Health Engineering	
Preliminary Report Air Pollution Surveillance Study Tucson, Arizona	1960	University of Arizona Tucson, Arizona	
Air Pollution in Greater Elmira, New York	1960	New York State Air Pollution Control Board Albany, New York	
A Pilot Study of Air Pollution in Washington, D. C.	1960	Washington, D. C., Dept. of Public Health and U.S. Dept. of HEW Public Health Service	
The Atmosphere Over Philadelphia, Its Behavior and Contamination	1950	Drexel Institute of Technology	Detailed analysis of 10 years of weather records for Philadelphia and discussion of high and low high volume air sampler and AISI sampler concentrations as related to meteorological conditions.
Report on Sampling Survey - Hudson, New York	1960	New York State Dept. of Health Bureau of Air Pollution Control Services, in Conjunction with The Columbia County Health Dept.	Five AISI tape samplers, and two wind speed and direction recording systems were used to evaluate levels of soiling contaminants and to attempt to correlate wind directions and possible contaminant sources in and around the survey area. The sampling period was approximately 3 months.
Fresno Air Pollution Study	1960	Air and Industrial Hygiene Laboratory Bureau of Air Sanitation Dept. of Public Health State of California	Survey covers two periods of one week duration in the months of September and December. Sampling was done for oxidant, nitric oxide, nitrogen dioxide, carbon monoxide, sulphur dioxide, hydrocarbons and particulate matter. Meteorological data including some temperature soundings are used in evaluating results.
Air Pollution in Lynchburg, Virginia	1961	Public Health Service (Region III)	Same as for state-wide air pollution appraisals.
Denver Metropolitan Area Air Sampling Survey	1961	Colorado State Dept. of Public Health	Survey covers 6-month period, with sampling of airborne particulate matter on 50 selected days. Field equipment included 6 AISI automatic strip filter paper samplers and 3 high volume filter paper samplers. Soiling characteristics, weight of suspended particulate matter and weight of benzene soluble organic matter in the suspended particulates was determined. Four gaseous pollutants were measured at a single station.

Table 1. (Cont'd) Selected List of Air Pollution Appraisals and Investigations of Limited Scope

DESIGNATION	DATE	RESPONSIBLE ORGANIZATION	SCOPE
In Quest of Clean Air for Berlin, New Hampshire	1962	Field Studies Branch Division of Air Pollution U.S. Public Health Service in cooperation with State of New Hampshire Department of Health and City of Berlin New Hampshire Health Dept.	A two month study with 10 instrumented air quality stations and three meteorological stations for the purpose of appraising nature, sources, extent, and effects of air pollution in Berlin, N.H. The major source of air pollutants is paper pulping and ancillary operations, including steam generations, of a single company.
A Pilot Study of Air Pollution Providence, Rhode Island	1962	Technical Assistance Branch Division of Air Pollution USPHS, in cooperation with Division of Air Pollution and Mechanical Equipment and Installations City of Providence	Survey covers two equal periods of 15 sampling days each at one station. Particulate pollutant measurements include soiling index, total suspended particulates and dustfall and gaseous pollutants measurements include those for sulfur dioxide, total oxidants, nitric oxide-nitrogen dioxide and carbon monoxide. The normalcy of the meteorological conditions during the sampling period is considered and air pollution potential for the city is discussed.
Air Pollution Measurement Study in Richmond, Virginia	1962	Richmond's Bureau of Air Pollution Control Virginia's State Dept. of Health and U.S. Public Health Service	Measurements of particulate matter concentrations by AISI Smoke Sampler, sulfur dioxide and oxidant levels, for a one-week period in January. Results are discussed in terms of wind speed and sunshine.
A Qualitative Survey of Atmospheric Pollution Potentials in Tiffin, Ohio	1962	Ohio Dept. of Health Division of Industrial Hygiene	Same as for state-wide air pollution appraisals.
A Pilot Study of Air Pollution in Birmingham, Alabama	1962	Technical Assistance Branch Division of Air Pollution U.S. Public Health Service in cooperation with Jefferson County Dept. of Health Alabama	Survey covers two, 4 week periods during the summer and fall. Air samples were collected for measurement of dustfall, suspended particulates, smoke shade, sulfur dioxide, nitrogen oxides, total oxidants, carbon monoxide and hydrogen sulfide. Meteorology is used in a discussion of air pollution potential.
A Pilot Study of Air Pollution in Jacksonville, Florida	1962	Technical Assistance Branch Division of Air Pollution U.S. Public Health Service in cooperation with Florida State Board of Health	Emission inventory data, meteorology and other information were used to determine if there is a general air pollution problem. To aid in accomplishing the objective gaseous and particulate pollutants were measured for one week in a downtown park. Also, there was an investigation to determine if fluorides and sulfur dioxide could be damaging vegetation. To accomplish the second objective, some additional sampling was conducted in the area where vegetation damage had occurred.

Table 1. (Cont'd) Selected List of Air Pollution Appraisals and Investigations of Limited Scope

DESIGNATION	DATE	RESPONSIBLE ORGANIZATION	SCOPE
Management of Dade County's Air Resources	1962	Technical Assistance Branch Division of Air Pollution and Dade County Dept. of Public Health	Existing data on population, agriculture, meteorology, sources of pollutants, present air quality, and details of a proposed refinery are used to estimate Dade County's air resources.
A Study of Denver Air Pollution	1962	Dept. of Atmospheric Science Colorado State University	This is a continuation and expansion of the above survey. It is primarily of a meteorological nature. Wind direction, wind speed and temperature observations were made at 5 special project stations and similar data was available from 6 stations maintained by cooperating agencies. These observations were supplemented by ground and aerial photography, by visual observations and measurements of turbidity. Observational results during 5 air pollution episodes are described.
Air Pollution in the National Capital Area		U.S. Dept. of HEW Public Health Service Maryland State Dept. of Health Virginia Dept. of Health	Uses available data on topography, meteorology, sources of pollution and summarizes information on air pollution measurements from 1931 to date.
Illinois	1956	Same as in Stern's Book, Page 591, (Vol. I)	Same as in Stern's Book, Page 591, (Vol. I)
Colorado	1962	" "	"
Georgia	1962	" "	"
South Dakota	1962	" "	"
Kansas	1962	" "	"
Air Resources of Utah	1962	Utah Legislative Council Air Pollution Advisory Committee	
The Program for Appraisal of the Air Quality of Maryland	1962	Maryland State Dept. of Health	Appraisal of air pollution potential, discussion of 8 station air pollution network. Measurements from high volume samplers, automatic smoke samplers and dustfall jars is presented.

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SITE SELECTION FOR A POLLUTANT SOURCE

D. H. Pack*

The question of pollution source siting is perhaps the most challenging problem in the entire pollution field because, if done properly, it can eliminate or very much reduce the problem before it begins. The scope of pollution source siting ranges from determining specific locations of exhaust vents or air intakes on roofs of buildings to the design of a model community with its parks, industrial areas, etc. The conventional viewpoint, "Here is a large plant - where shall we put it?" is far too restrictive. There is something to be gained from the use of meteorology over the whole gamut of source location including determining the best relationship of the meteorology to the effluent type and the sources of pollution.

One should look into the philosophy of what we are trying to do. Air pollution is important only because of people. Air pollution that does not effect man, his animals and plants is of very little concern to us. The major reason for interest in air pollution results from urbanization and insufficient room for pollutants to be distributed.

Many of us, the technicians and specifically the meteorologists, are too apt to look at a problem and say, "Here is the solution." When presenting this solution to management, government or whoever is responsible for making decisions on pollution, we may be sure it will not be used if it is based solely on one narrow discipline. Such a solution may be uneconomical or it may be politically or psychologically impossible. For these reasons, it is incumbent on every individual that, if the data permit, he offer a variety of solutions and be able to discuss the consequences of adopting any particular one so that when a decision is made, some rational use will have been made of the environment to dilute material. We are not talking about absolute solutions; there is just too much involved for that.

Air pollution problems are now so complex that the air pollution control officer, chemist, meteorologist, etc., probably cannot know all the various factors that must be brought to bear on pollution siting. The astute individual will go to his counterpart beforehand for consultation or advice. We must require ourselves to be flexible and ingenious in providing advice since we are generally consultants not management. As a consultant, we must know as much about the problem as we can, bring to bear all the tools we can lay our hands on, and present a series of alternative answers. Several areas which must be considered are:

I Can weather be designed out of problem?

II What is the scope for site choice?

A Unlimited

B Restricted to specific large area (e.g., size of a state)

C Two or three alternate but fixed locations

D One location

III What is the pollution problem?

A What is the nature of the pollutant?

1 Toxic

a Maximum Allowable Concentration (MAC)

b Permissible chronic concentrations?

c Method of uptake

Inhalation

Ingestion

Via food chain

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2 Nuisance

a Odors

b Dust (can be more than nuisance)

c Soot

3 Environmental behavior

a Decay with time

Photolysis

Radioactive decay

b Deposition

c Reactions (e.g., SO_2 - H_2SO_4)

d Synergistic effects in presence of other materials

B Single or Multiple Source

C Area, point, surface, elevated source? (If elevated how high?)

D Release Characteristics

1 Temperature, velocity, gas, particulate size, etc.

2 Seasonally influenced?

3 Continuous or intermittent - If intermittent what are return periods, hold-up facilities, etc.?

4 The potential source (i.e., the accident problem)

Nuclear reactors, chemical storage areas, etc. (operation chlorine)

E What is "downwind?" (Receptor characteristics)

1 Permanent populations (e.g., residential areas)

2 Transient populations (daytime work force, seasonal populations as at resorts, etc.)

3 Vegetation types (sensitive to potential pollutant? pine trees -SO_2)

4 Animals (milk shed and I^{131})

F Control Possibilities and Plans (Evaluation and cost analyses)

1 Full time control

2 Part time

a Operational characteristics - how much lead time required?

b Hold-up facilities (what is needed?)

3 Meteorological control (generally considered last resort for commercial operations) common practice in AEC, DOD

IV What is the meteorological problem?

A Area Patterns

1 Seasonal changes and variations

2 Synoptic changes and variations

B Local Patterns

1 Terrain controlled anomalies

a Mountain-valley circulations

b Sea and lake shore circulations

c Channelled flow

2 Urban effects (if any)

C Estimation of Effects of Pollution - Transport and Diffusion Vs. Ventilation (Volumetric Approach)

1 Single source

a Close in (0-5 miles) in open terrain - transport and diffusion b Long distances and in urban areas - ventilation

c Massive single source - combine T and D and ventilation

2 Multiple sources

a Transport and diffusion (e.g., Nashville model, receptor models) - requires source inventory

b Ventilation - (e.g., Duckworth, Bell in California)

V METEOROLOGICAL TOOLS

A Area Data

1 Published summaries

Examples - airways atlas, inversion study, mixing depth study, stagnation studies, climatologies of particular places.

2 Special unpublished tabulations - U.S. Weather Bureau, National Weather Records Center

B Local Data - Available from Many Sources

1 Summarized and published

a Local climate data - WB

b Station climatologies

2 Special studies

a Reactor hazard studies (particularly as sources of data)

b Industrial studies

c Military installations

3 Local non-WB observations

a Military

b Commercial (e.g., approximately 100 recording anemometers have been located between Richmond, Va. and New York City)

C Special On-Site Studies

1 Short term "scoping" studies

2 Longer term (1-2 year) studies

3 Permanent (or quasi-permanent) programs

4 Data collection

a Wind

Frequency, fluctuation characteristics, spatial variations

b Wind and temperature gradient

c Multiple station studies

d Tracer studies

1) Balloons (e.g., Sakagami, Gifford, Pack at Shippingport, Pa.)

2) Controlled release and sampling of gases and/or particulates (SO_2, FP, Uranine)

3) Sources of opportunity - particularly use of smoke photos

4) Tetroons - for long range trajectories or major pollution problems

VI SPECIAL PROBLEMS

A Conspicuous Sources

B Adding Sources to "Saturated" Atmosphere

C Long Range Travel Problems (single source such as western states smelters)

D Recirculation of Pollutants

E Controlled Release - When and How Much

F The Rare or "One-Shot" Pollution Problem (e.g., Nuclear Reactor Accidents)

VII PROBABILITIES AND PERSISTENCE IN POLLUTION SOURCE SITING

A Lapse Rate

1 Large area - stagnation episodes

2 Point source - (Hosler's Monthly Weather Review study)

Inversion Duration Probability (hours)

	50%	10%	1%
Hanford, Wash.	13	17	22
Shippingport, Pa.	4.5	15	24
Middletown, Conn.	14	19	27
Idaho Falls, Ida.	16	19	22

B Wind

22 1/2° Sector
Direction Duration Probability (hours)

	50%	10%	Max.
Laredo, Texas	2.2	6.7	36
Denver, Colo.	2.0	6.3	22
San Diego, Calif.	2.7	4.0	35

112 1/2° Sector
Direction Duration Probability (hours)

	50%	10%	Max.
Laredo, Texas	4.6	40	300
Denver, Colo.	3.6	16	49
San Diego, Calif.	1.5	18	140

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ATMOSPHERIC TRACERS
AND URBAN DIFFUSION EXPERIMENTS

J. L. Dicke*

I ATMOSPHERIC TRACERS

Dispersion of pollutants by atmospheric diffusion and transport processes has received considerable theoretical treatment and there are several operational techniques available for empirical studies of diffusion on various distance scales. Figure 1 lists some of the tracers and the distances over which they have been used. Another class of tracer materials now being developed includes various halogenated compounds such as Freon 12, sulfur hexafluoride (SF_6) and bromotrifluoromethane.(7)

The suitability of any material for a tracer may be assessed by its ability to meet a number of requirements, several of which have been enumerated by Leighton.(4)

1 The material must possess a specific property, not duplicated by any other substance normally present in the atmosphere, which will permit its detection in extremely small amounts.

2 There should be a simple, rapid, sensitive and convenient method for the quantitative determination of the small amount of material.

3 The material should be available at reasonable expense in uniform lots large enough for the desired use and it should not deteriorate during storage.

4 The tracer should be readily and quantitatively dispersible into the atmosphere at controlled rates.

5 The tracer should be stable while in the atmosphere and its dispersion by atmospheric turbulence should be essentially that of an inert gas.

6 The tracer material should retain its specific property at least through the sampling and assessment operations.

7 The tracer should be safe to handle and non-toxic to man, animals and plants.

Atmospheric tracers can be used for a variety of experiments: To prove transport of material from one location to another such as in the New York - New Jersey area where fluorescent particles (FP) and balloons were used to prove interstate transport of air pollution.(8) To obtain empirical data on a practical problem such as penetration of chemical agents into forests or cities without using the actual chemical.(2) To investigate the actual urban area effects on dispersion parameters(6) and to evaluate σ_y and various topographic influences.(3) Recently Niemeyer and McCormick(5) have shown that both SF_6 and FP can be used as tracers to obtain quantitative diffusion data over ranges in excess of 100 km, for which precise knowledge of dispersion is now almost non-existant.

II URBAN DIFFUSION EXPERIMENTS

A St. Louis

Diffusion studies to provide direct experimental values of dispersion parameters over urban areas were first conducted in St. Louis in 1962 and 1963.(6) FP was disseminated in a series of trials under a wide range of meteorological conditions to determine the effects of the urban area on dispersion. Several sampling arcs were laid out as in Figure 2 and instrumented with rotorod, drum-pulsed, and membrane filter samplers, Figure 3 to collect the FP both on a total and sequential time basis.

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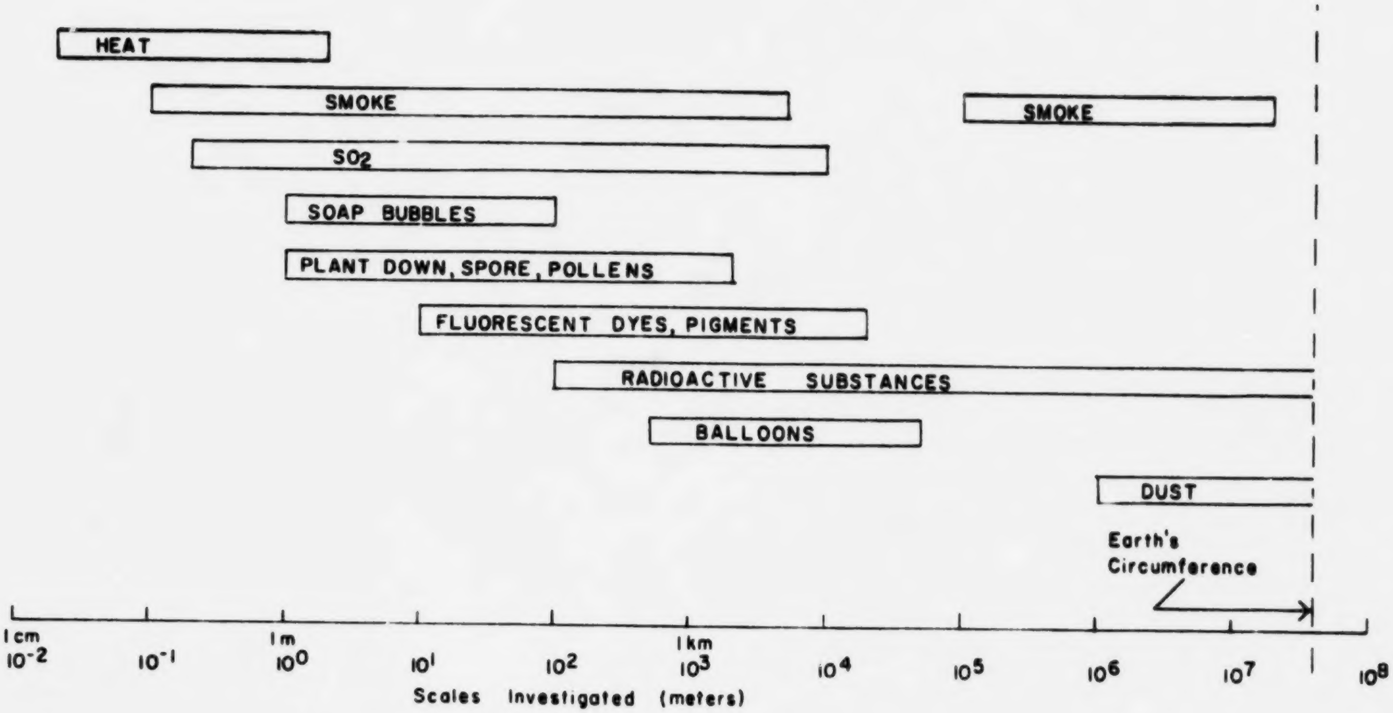
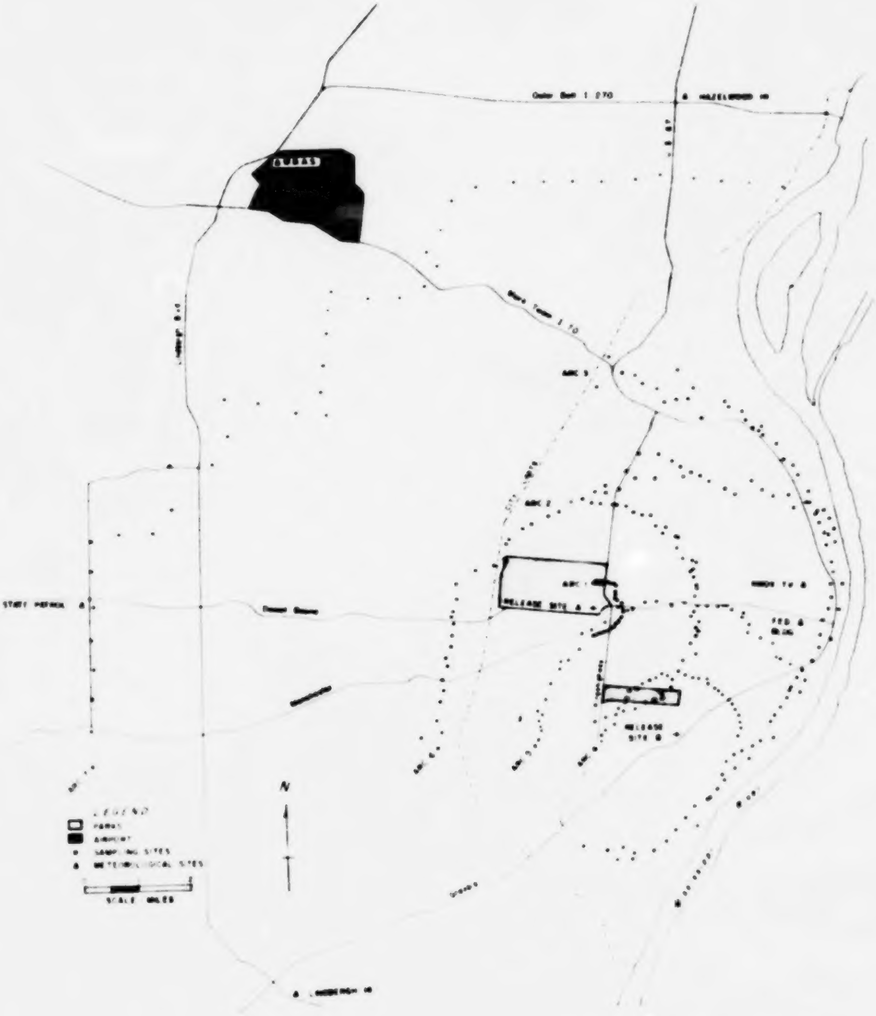


Figure 1. TRACERS USED IN ATMOSPHERIC TURBULENCE AND DIFFUSION


Outer Belt I 270
HAZELWOOD HI
Mark Twain I 70
ARC 3
ARC 2
ARC 1
RELEASE SITE A
RELEASE SITE B
FED B BLDG
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LEGEND
PARKS
AIRPORT
SAMPLING SITES
METEOROLOGICAL SITES
SCALE MILES
LINDBERGH HI

Figure 2. ST. LOUIS, MISSOURI, DIFFUSION STUDY MAP

Reproduced from best available copy.

[illegible]

[illegible]

[illegible] sampler

[illegible] EQUIPMENT

Tentative results of this study indicate that horizontal dispersion (σ_y) over a city is not markedly different from dispersion over open country, provided that an initial plume dimension comparable to the size of a city building is assumed. The vertical dispersion (σ_z) over a city during the daytime is comparable to that observed over open country. Vertical dispersion during the evening over an urban area is much greater than that observed over open country; the data suggest the formation of a slightly unstable layer of air over the city as the cool air flowing in from the country is warmed from below.

B Cincinnati

The diffusion studies in Cincinnati$^{(5)}$ have had two objectives: first to develop sampling and analysis techniques for several halogenated atmospheric tracers and second to obtain quantitative diffusion data over the range of one to several hundred kilometers.

Short range experiments on the grounds of the Gest Street Facility of NCAPC over distances up to 200 meters were conducted using two or three halogenated gaseous compounds together with FP. Rotorods and sequential drum samplers were used to collect the FP while the gases were collected in Saran bags for gas chromatographic analysis. The results showed that the halogenated gases were satisfactory tracer materials.

The long range experiments were conducted over the rolling terrain of northern Kentucky and southern Ohio. Meteorological conditions were chosen such that steady southerly winds would persist for at least six hours at high enough speeds to move the tracer cloud across the sampler arcs before marked diurnal stability changes occurred. Two or three sampling arcs were spaced about 30 to 40 kilometers apart depending on available highways. The centerline of each arc was determined by predicting the trajectory of a transponder-equipped tetroon which was released from the tracer dissemination site shortly before the tracers were released and tracked by radar.

Another objective of these tests has been to determine the magnitude of non-meteorological errors. This has been shown to be as high as 50%. The primary causes for errors lie in the analytical techniques, loss of particulate tracer strength, sampling errors and uncertainties in source strength.

The preliminary results indicate that the horizontal dispersion (σ_y) values are within 10-15% of the σ_y values for neutral stability conditions as presented in Section III of this manual. In addition the feasibility of using a gaseous tracer over a 75 mile range has been demonstrated.

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METEOROLOGICAL MODELS FOR URBAN AREAS

D. B. Turner*

I DEFINITION OF A DISPERSION MODEL

A A dispersion model is a mathematical description of the meteorological transport and dispersion processes combined with:

1 The necessary meteorological parameters during a particular period, and

2 An inventory of emissions to the atmosphere of the pollutant of interest to yield,

Estimates of concentrations of the particular pollutant for specific locations and time periods.

B To verify a model actual concentrations of the particular atmospheric pollutant must be measured for comparison with those calculated

C Considering the structure of a model:

1 The mathematical description may be a dispersion equation such as the Gaussian or bivariate normal equation with additional provisions for considering wind direction.

2 The meteorological input parameters usually include wind direction, wind speed and stability. The environmental temperature lapse rate and a vertical limit to mixing may also be incorporated.

3 The emission inventory will include the locations of and amounts emitted from all sources of the pollutant of interest for the time periods needed.

II TYPES AND USES OF MODELS

A Short-time period model (1 hour to 1 day)

1 Diffusion Calculations - Estimate concentrations where it is impractical to sample such as over rivers or lakes or at distances above the ground.

*2 Control - Determine the amount of decrease required for pollutant sources under particular conditions or the necessary decrease in sources required when a predetermined alert level has been reached.

*3 Sampling - Location of mobile sampling teams when a pollution alert occurs.

B Climatological model (long time periods; months of years, or particular times of day for each season over a number of years).

1 Control - Aid in developing emission standards based on air quality standards.

2 Sampling - Locate permanent samplers strategically.

3 Planning - Location of sources with respect to source emission amounts and potential receptors.

III URBAN AIR POLLUTION DIFFUSION MODELS AND RESULTS

A Pooler[1] - Nashville, Tennessee

Spatial distribution of SO_2 concentrations for periods of a month.

1 The Weather Bureau airport wind rose was used with a diffusion equation assuming a mean stability.

2 SO_2 calculations and observations were compared at about 120 locations for five months (600 comparisons).

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*A2 and 3 both require forecasts of mesometeorological parameters.

*Meteorologist, Air Resources Cincinnati Laboratory, ESSA, NAPCA, Cincinnati Ohio

3 50% of the observed concentrations were between 0.8 and 1.25 times those calculated. 95% were within a factor of two.

B Turner - Nashville, Tennessee

Spatial distribution of SO_2 concentrations for 2-hour and 24-hour periods.

1 Mean wind velocity and atmospheric stability were determined for each 2-hour period.

2 24-hour concentrations were obtained from averaged 2-hour concentrations and 35 24-hour periods were modeled. SO_2 calculations and observations were compared at 32 locations on a 24-hour basis and at seven locations on a 2-hour basis. (1000 24-hour comparisons).

3 58% within 1pphm (error of measurement) 70% within a factor of 2.

C Clarke - Cincinnati, Ohio

Temporal variations of several pollutants at a single receptor location.

1 Sources over four ranges of distance from the single receptor location.

2 Solutions obtained by graphical techniques.

3 Comparison of 24-hour concentrations

Pollutant	Number of data pairs	Correlation	Number within a factor of 2
SO_2	24	0.71	63%
NO_x	19	0.67	95%
SO_2	19	0.81	47%

D Miller and Holzworth - Los Angeles, Nashville, Washington, D.C.

Average NO_x concentrations over Los Angeles and SO_2 concentrations over Nashville. Point NO_x concentrations at the Washington, D.C., CAMP station.

1 Minimum (afternoon) and maximum (morning) average concentrations over the urban area.

2 Results

Afternoon	Number	Correlation coefficient	
Los Angeles	36	.88	
Nashville	31	.84	
Washington	41	.83	
Morning			
Los Angeles	35	.80	over
Nashville	31	.84	estimated

3 Sequel comparing the statistical and analytical results for NO_x (Miller, 1967).

E Other

1 Szepesi - Hungary

2 Koogler - Jacksonville, Florida

3 Fortak - Bremen, Germany

4 Nester - Germany

IV CURRENT ACTIVITY IN MODELING

A New York - New York University (2) (25)

Emission Inventory

Sea Breeze

B St. Louis - D. B. Turner - NAPCA

Plume Rise - Large Sources

Diurnal Variation of Emissions

C Chicago - Dept. of Air Pollution Control and Argonne National Laboratory

Source inventory, backed by city ordinance

Telemetered SO2 and wind information from 8 sites.

D Air Quality Control Regions - NAPCA Long-term Control Strategies - Air Pollution Episode Plans (22)

E Los Angeles - Lamb and Neiburger (24), Lamb (25)

Differential equation solutions that do not involve the well-known normal bivariate formula are proposed in an urban model.

F Photochemical Models - Eschenroeder and Martinez (26)

Finite difference methods for solving k-theory differential equations include atmospheric chemical reactions - secondary pollutant formation.

G Summary

Symposium: Multiple Source Urban Diffusion Model. The Proceedings contain a valuable set of 14 papers and a discussion reflecting the state of the art in modelling to 1970. (23)

V FURTHER RESEARCH NEEDS

A Investigate dispersion for longer travel times.

B Include chemical reactions and removal rates in dispersion estimates.

C Estimate dispersion for longer distances and at higher levels in the atmosphere over a variety of atmospheric and emission conditions.

D Complete the formidable task of obtaining emission inventories, including diurnal variations of emissions.

E Account for the variation of dispersion with height.

F Determine plume rise more accurately, especially from large sources.

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SOURCES OF METEOROLOGICAL DATA

D. B. Turner*
J. L. Dicke**

It is necessary in the consideration of most air pollution problems to obtain meteorological information. Frequently a special observational program must be initiated. There are also situations where current or past meteorological records from a Weather Bureau station will suffice. The following outline provides a brief insight into the types of observations taken at Weather Bureau stations and some of the summaries compiled from this data.

I OBSERVATIONS AND RECORDS

A Surface

1 First order stations

There are 200 Weather Bureau stations where 24 hourly observations are taken daily. The measurements taken are: dry bulb temperature and wet bulb temperature (from which dew point temperature and relative humidity are calculated), pressure, wind direction and speed, cloud cover and visibility. These observations are transmitted each hour on weather teletype circuits and are entered on a form with one day to each page. The original is sent to the National Climatic Center (NCC) in Asheville, North Carolina, and a duplicate maintained in the station files. Each station also maintains a climatological record book where certain tabulations of monthly, daily, and hourly observations are recorded. (See Part Two).

2 Second order stations

These stations usually take hourly observations similar to the first order stations above but not throughout the entire 24 hours of the day.

3 Military observations

Many military installations, especially Air Force Bases, take hourly observations. These are transmitted on military teletype circuits and therefore not available for general use. No routine publications of these data is done. Records of observations are sent to NCC where special summaries can be made by use of punched cards.

4 Supplementary airways reporting stations

These stations are at smaller airports. The observations are not at regular intervals, usually being taken according to airline schedules at the airport. These observations are not published and not on punched cards. Original records are sent to NCC, however.

5 Cooperative stations

There are about 10,000 of these stations manned for the most part by volunteer observers. The observations are taken once each day and consist generally of maximum and minimum temperatures and 24 hour rainfall. Observations are recorded on a form with one month to a page. The original is sent to NCC, a carbon sent to the state climatologist, and a carbon maintained at the station. A few cooperative stations have additional data on evaporation and wind. However, the wind observations are taken at only a few inches off the ground and are of use mainly in connection with the evaporation measurements.

6 Fire weather service stations

There are a number of special stations maintained during certain times of the year in forested regions where measurements of wind, relative humidity, and cloud cover are taken. These are not generally on punch cards or summarized.

B Upper Air

There are between 60 and 70 stations in the contiguous United States where upper air observations are taken twice daily (at 0000 GCT and 1200 GCT) by radiosonde balloon and radio direction-finding equipment. The measurements made are temperature, pressure, and relative humidity with height and wind speed and direction. Since these data are obtained primarily for knowledge of the large scale meteorological pattern and have relatively little refine-

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*Meteorologist, Air Resources Field Research Office, ESSA

**Meteorologist, Air Resources, Cincinnati Laboratory ESSA, Office of Manpower Development, EPA ment in the lower 2 to 3 thousand feet of the atmosphere, they are of limited use in air pollution meteorology. These observations are transmitted by teletype and original records sent to NCC where these data are published. (See Part Two).

II CLIMATOLOGICAL DATA

There are a number of routine and special publications available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, that are useful in air pollution. A number of these are listed in Price List 48, available from the Superintendent of Documents.

Of principal interest in air pollution are the elements of wind and stability in relation to transport and diffusion, degree days in relation to source emissions from space heating, solar radiation which affects stability and atmospheric reactions, and precipitation affecting removal of pollutants. Following are listed the publications of main interest in air pollution. For more detailed information on these and other publications see "Selective Guide to Published Climatic Data Sources prepared by U.S. Weather Bureau" published in 1969.

A Routinely Prepared Data

1 Daily weather map

The series of maps issued daily including Sundays and holidays at Washington, D.C. consists of five maps printed on one page, 24 inches by 19 inches. Observations taken at 1 a.m. EST are used to draw a surface map with isobars and frontal positions. The other 4 smaller maps show: 1) the frontal and isobaric pattern 12 hours prior to the other map, 2) 500-millibar pressure chart prepared from radiosonde observations at 7 p.m. EST on the previous day, 3) highest and lowest temperatures for the previous 24 hours, and 4) precipitation areas and totals for the previous 24 hours. The price of this publication is \$9.60 per year or \$2.40 for 3 months. The maps are sent by first class mail and usually are available in the Eastern U.S. 60 to 84 hours after map time.

2 Local climatological data

These data are published individually for each station and include 3 issues discussed below. The subscription price is \$1.50 per year for all three issues.

a Monthly Issue LCD

This issue, illustrated in Figure 1, gives daily information on a number of meteorological variables and monthly means on temperature, heating degree days, pressure and precipitation. On the reverse side are tabulated observations at 3-Hourly Intervals; see Figure 2. Tabulation of observations for each hour of the day was discontinued after December 31, 1964. This publication is usually available between the 10th and 15th of the following month.

b LCD Supplement (monthly)

This issue is available only for stations having 24 hourly observations daily until December 31, 1964 when publication was stopped. It contains frequency tables illustrated in Fig. 3. For air pollution investigations, Tables B,E,F, and G would be of greatest interest (Frederick, 1964). The Supplement is usually available from 20 to 40 days after the end of the month.

c LCD with Comparative Data (annual)

This issue, published annually, has a table of climatological data for the current year and a table of normals, means, and extremes for a longer period of record. This issue is usually available between 45 and 60 days after the end of the year.

3 Northern Hemisphere Data Tabulations

This publication, issued daily, contains approximately 30 pages of surface synoptic observations and upper air observations. The surface data are for one hour only (1200 GCT). In this publication the radiosonde information is of principal interest in air pollution meteorology. A portion of a page of radiosonde data is illustrated in Figure 4. The data are available only in microforms. The subscription price is \$5.00 per month, separate daily copies 25 cents. This publication is usually available 8 to 10 months after the date of the observations.

4 Climatological Data - National Summary

This publication of approximately 50 pages, issued monthly, contains a narrative summary of weather conditions, climatological data (similar to those given in each station's LCD) in both English and metric units, mean monthly radiosonde data, and solar radiation data. Also included are a number of maps of the United States showing spatial distribution of temperature, precipitation, solar radiation and winds. The mean radiosonde and solar radiation data are the main interests of this publication in air pollution meteorology. A portion of a page of mean radiosonde data is illustrated in Figure 5. An annual issue of this publication is also available. Subscription prices are 20 cents for monthly and 40 cents for annual issues; yearly, including monthly and annual; $2.50. Monthly issues are available from 4 to 6 months after the month of observation.

5 Climatological Data (by State)

This summary, issued monthly and annually contains data mainly on temperature and precipitation. This will only occasionally be of use to the air pollution meteorologist. Subscription price is 20 cents per monthly or annual copy or $2.50 per year for both monthly and annual issues. This publication is usually available 2 to 4 months from the month of observation.

6 Selected climatic maps

This publication consists of 30 U.S. maps of various meteorological parameters such as: maximum and minimum temperature, heating and cooling degree days, precipitation, relative humidity, solar radiation, and surface wind roses for January and July together with the annual wind rose. Wind data are presented for 74 locations within the contiguous U.S. A list of the basic Climatic Maps from which the generalized maps of this publication are taken is included.

B Summaries

1 Summary of Hourly Observations

This series of publications, Climatography of the United States, No. 82- , Decennial Census of United States Climate, has been prepared for over 100 Weather Bureau stations where 24 hourly observations are recorded each day. One issue is prepared for each station. Where records are sufficiently long the ten year period 1951 - 1960 has been considered. For others the 5 year period 1956 - 1960 has been summarized. This series supersedes the series, "Climatography of the United States" No. 30- , a 5 year summary published in 1956. A set of tables similar to tables A through E in the LCD Supplement are given for each month (See Figure 6) and for the entire period (See Figure 7). The price of this publication is 10 cents per copy and is prepared separately for each station. This series was temporarily discontinued as of May 1, 1965.

2 Climatic Guide

This series of climatological publications contains a wealth of climatological information useful to the air pollution meteorologist fortunate enough to have had one prepared for his city. Of major interest to air pollution meteorologists, are tables of wind frequencies, solar radiation and degree days.

The guides that have been published and the year of issue are:

Baltimore, Maryland	1958
New York City	1958
Seattle, Washington	1961
Chicago, Illinois	1963
Houston, Galveston, Texas	196[illegible]

The price of this publication varies between 30 and 40 cents per copy.

3 Climatic Summary of the United States - Supplement for 1931 - 1952.

This summary, issued separately by state, contains tables of monthly and annual precipitation, snowfall, and temperature by stations in the state. The price of this publication ranges from 20 cents to 70 cents per copy.

4 Terminal Forecasting Reference Manual

This manual, published by station, describes the weather conditions at the station, contains information on local topography, visibility effects due to fog and smoke, ceiling, precipitation, special weather occurrences, and mean wind and visibility conditions. Numerous charts are included summarizing the above elements. Of special interest are surface wind roses by month and a wind rose chart related to restricted visibility conditions. A topographic and smoke source map for the station is included. The price per copy is 10 cents.

5 Key to Meteorological Records Documentation

This series of publications was established to provide guidance information to those making use of observed data. A recent addition to this series No. 4. 11, "Selective Guide to Published Climatic Data Sources prepared by U.S. Weather Bureau" (1969) all is extremely useful to anyone contemplating use of climatic data. The addresses of the state climatologists are given inside the back cover.

The series No. 1. 1 title Substation History and issued by state contains information regarding history of station locations, type and exposure of measuring instruments, location of original meteorological records, where published, and dates of first and last observations. The price of this publication per state is $1.50.

III NATIONAL WEATHER RECORDS CENTER

The National Climatic Center was established in Asheville, North Carolina, in 1951 as the national archives for weather records. The files at the center contain 100,000 cubic feet of original records,more than thirty thousand reels of magnetic tape, and over 230,000,000 punched cards (Crutcher, 1964). In order to take a minimum of storage space, some of the punched cards have been microfilmed using FOSDIC (Film Optical Sensing Device for Input to Computers). This places the images of 12,000 punched cards on 100 ft. of 16 mm.film. An optical reader in combination with a card punch is used to recover the data. A reader to transfer data directly to magnetic tape is under development. For preparation of summaries, the Climatic Center has a RCA Spectra 70/45. Original manuscripts can be copied by microfilm, photocopy, xerox, microprints or microcards and furnished to users at the cost of reproduction. Special summaries are also prepared at cost for individuals or companies. A cost estimate for a specific job will be prepared on request. Inquiries may be addressed to Director, National Climatic Center, NCAA, Federal Building, Asheville, N.C., 28801.

Magnetic tape and punched cards can also be furnished to users with their own data processing equipment. Examples of three types of punched cards, the Hourly Surface Observation, Type 1; the Summary of the Day Card, Type 3; and the Winds Aloft Observations, Type 4 are shown in Figure 8. However, coding procedures for cards change, such as reporting winds to the nearest 10° (36 points) on January 1, 1964 and thereafter. Previously, winds were reported to 16 points of the compass. If a period of study spans one of these changes considerable difficulty may be encountered. A publication indicating some of the work of the NCC is: Climatology at Work (1960).

REFERENCES

1 Barger, G.L., Editor, Climatology at Work. Superintendent of Documents, Government Printing Office, Washington, D.C., 20402. 1960. 65 cents.

2 Crutcher, H.L. The National Weather Records Center. Seminar on Human Biometeorology, Public Health Service Publication No. 999-AP-25. 1967.

3 Frederick, R.H. Weather Data for Air Pollution-Available, Analyzed and Inexpensive. J. of Air Pollution Control Assoc. 14:2, 60-65. 1964.

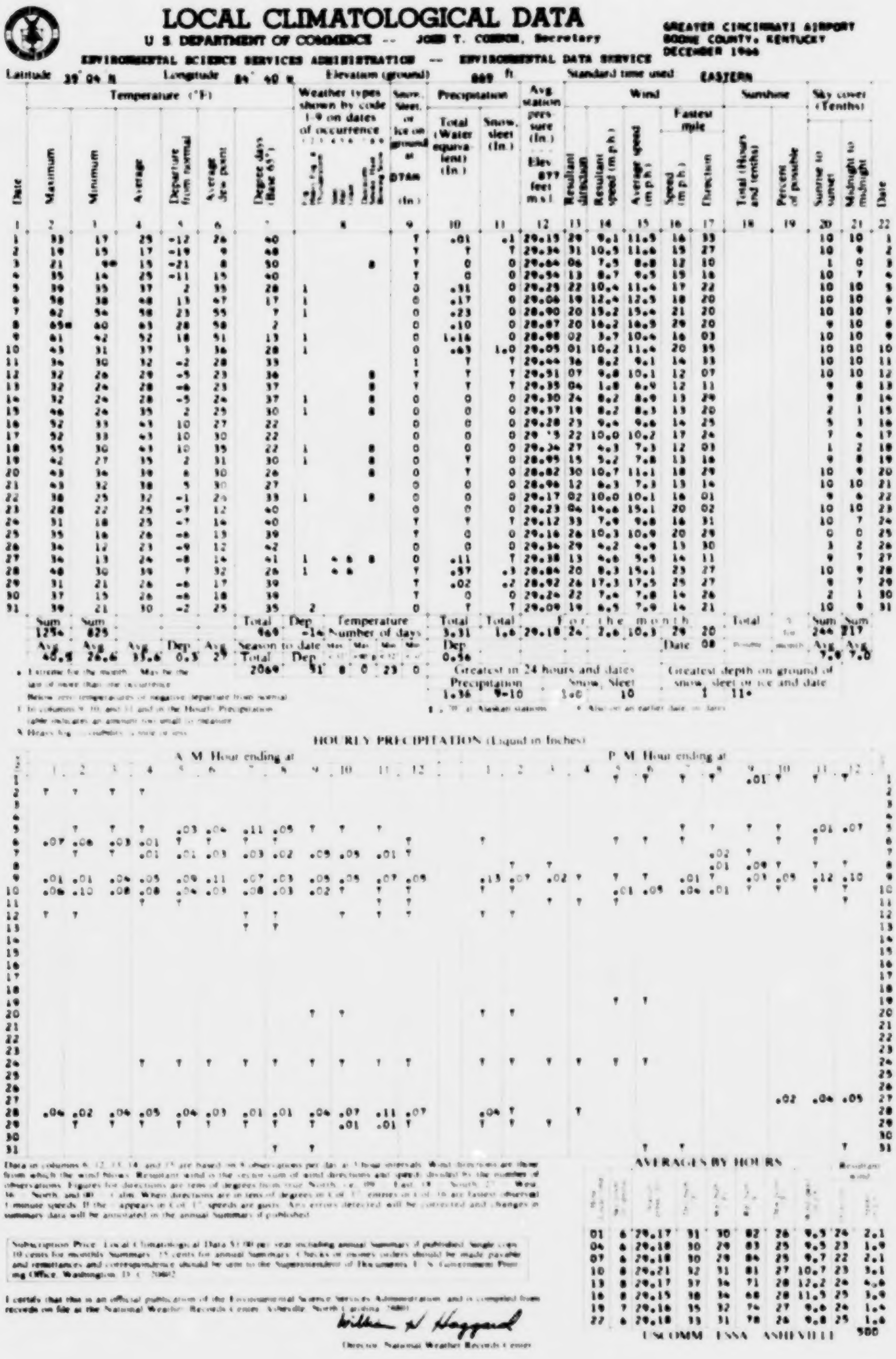
4 Selective Guide to Climatic Data Sources. Key to Meteorological Records Documentation No. 4. 11. Prepared by Staff, NCC, Asheville, N.C. Superintendent of Documents, Government Printing Office, Washington, D.C., 20402. 1969 $1.00

5 Superintendent of Documents, Selected Climatic Maps of the United States. U.S. Government Printing Office, Washington, D.C. 20402. 25 cents

6 U.S. Superintendent of Documents. Weather, Astronomy, and Meteorology. Price List 48. Government Printing Office. Washington, D.C., 20402.

7 U.S. Navy, NAVAER 50-1C-534. Guide to Standard Weather Summaries. January 1959 with Change No. 1, 15 July 1960.

8 U.S. Dept of Commerce, Weather Bureau. Inventory of unpublished tabulations. Washington, D.C. 1954. 80 cents.



LOCAL CLIMATOLOGICAL DATA

U S DEPARTMENT OF COMMERCE -- JOHN T. CONNOR, Secretary
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION -- ENVIRONMENTAL DATA SERVICE

GREATER CINCINNATI AIRPORT
BOONE COUNTY, KENTUCKY
DECEMBER 1966

Latitude 39° 04' N Longitude 84° 40' W Elevation (ground) 869 ft Standard time used EASTERN

Date	Temperature (°F) Maximum	Minimum	Average	Departure from normal	Average dew point	Degree days (Base 65°)	Weather types shown by code 1-9 on dates of occurrence	Snow, Sleet, or Ice on ground at 07AM (In.)	Precipitation Total (Water equivalent) (In.)	Snow, sleet (In.)	Avg. station pressure (In.) Elev. 877 feet m.s.l.	Wind Resultant direction	Resultant speed (m.p.h.)	Average speed (m.p.h.)	Fastest mile Speed (m.p.h.)	Fastest mile Direction	Sunshine Total (Hours and tenths)	Percent of possible	Sky cover (Tenths) Sunrise to sunset	Midnight to midnight	Date
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	33	17	25	-12	26	40		T	.01	.1	29.15	20	9.1	11.5	16	33			10	10	1
2	19	15	17	-19	9	48		T	T	T	29.34	31	10.5	11.6	15	27			10	9	2
3	21	9*	15	-21	8	50	8	T	0	0	29.64	06	7.5	8.8	12	10			1	0	3
4	35	14	25	-11	15	40		T	0	0	29.54	13	8.7	9.5	15	18			10	7	4
5	39	35	37	2	35	28	1	0	.31	0	29.25	22	10.4	11.6	17	22			10	10	5
6	58	38	48	13	47	17	1	0	.17	0	29.06	19	12.4	12.5	18	20			10	10	6
7	62	54	58	23	55	7	1	0	.23	0	28.90	20	15.2	15.4	21	20			10	10	7
8	65*	60	63	28	58	2		0	.10	0	28.87	20	16.2	16.9	29	20			9	10	8
9	61	42	52	18	51	13	1	0	1.16	0	28.98	02	3.7	10.6	16	03			10	10	9
10	43	31	37	3	36	28	1	0	.63	1.0	29.05	01	10.2	11.6	20	35			10	10	10
11	34	30	32	-2	28	33		1	T	T	29.44	36	8.2	9.1	14	33			10	10	11
12	32	26	29	-5	23	36	8	T	T	T	29.51	07	9.8	10.1	12	07			10	10	12
13	32	24	28	-6	23	37	8	T	T	T	29.35	04	1.8	6.9	12	11			9	8	13
14	32	24	28	-5	24	37	1 8	0	0	0	29.30	24	8.2	8.9	13	29			9	8	14
15	46	24	35	2	25	30	1 8	0	0	0	29.37	19	8.2	8.3	13	20			2	1	15
16	52	33	43	10	27	22		0	0	0	29.28	23	9.4	9.6	14	25			5	3	16
17	52	33	43	10	30	22		0	0	0	29 '5	22	10.0	10.2	17	24			7	4	17
18	55	30	43	10	35	22	1 8	0	0	0	29.34	27	4.3	7.3	12	03			1	2	18
19	42	27	35	2	31	30	1 8	0	T	0	28.95	15	5.2	7.8	13	18			9	8	19
20	43	34	39	6	30	26	8	0	T	0	28.82	30	10.7	11.1	18	29			10	9	20
21	43	32	38	5	30	27		0	0	0	28.96	12	6.3	7.3	13	14			10	10	21
22	38	25	32	-1	24	33	1 8	0	0	0	29.17	02	10.0	10.1	16	01			9	6	22
23	28	22	25	-7	12	40		0	0	0	29.23	04	14.6	15.1	20	02			10	10	23
24	31	18	25	-7	14	40		T	T	T	29.12	33	7.9	9.8	16	31			10	7	24
25	35	16	26	-6	13	39		T	0	0	29.16	26	10.3	10.9	20	29			0	0	25
26	34	12	23	-9	12	42		0	0	0	29.36	29	4.2	4.9	13	30			3	2	26
27	34	13	24	-8	14	41	1 4 6 8	0	.11	T	29.38	13	4.6	5.5	14	11			9	7	27
28	48	30	39	7	32	26	1 4 6	T	.57	.3	28.84	20	8.3	15.1	23	27			10	9	28
29	31	21	26	-6	17	39		T	.02	.2	28.92	26	17.3	17.5	25	27			9	7	29
30	37	15	26	-6	18	39		T	0	0	29.24	22	7.4	7.8	14	26			2	1	30
31	39	21	30	-2	25	35	2	0	T	T	29.09	19	6.5	7.9	14	21			10	9	31

Sum 1254	Sum 825				Total 969	Dep -16	Temperature Number of days				Total 3.31	Total 1.6	For the month 29.18	26	2.6	10.3	29	20
Avg 40.5	Avg 26.6	Avg 33.6	Dep 0.5	Avg 27	Season to date Total 2069	Dep 31	8	0	23	0	Dep 0.56						Date 08	

Sunshine Total	% for month	Sky cover Sum 246	Sum 217
		Avg 7.9	Avg 7.0

Greatest in 24 hours and dates: Precipitation 1.36 9-10; Snow, Sleet 1.0 10

Greatest depth on ground of snow, sleet or ice and date: 1 11+

* Extreme for the month - May be the last of more than one occurrence

Below zero temperatures or negative departure from normal

T In columns 9, 10, and 11 and in the Hourly Precipitation table indicates an amount too small to measure

& Heavy fog: visibility ¼ mile or less

‡ 70° at Alaskan stations

+ Also on an earlier date, or dates

HOURLY PRECIPITATION (Liquid in Inches)

Date	A.M. Hour ending at 1	2	3	4	5	6	7	8	9	10	11	12	P.M. Hour ending at 1	2	3	4	5	6	7	8	9	10	11	12	Date
1																	T	T	T	T	.01	T	T	T	1
2	T	T	T	T																					2
3																									3
4																									4
5		T	T	T	.03	.04	.11	.05	T	T	T								T	T	T	T	.01	.07	5
6	.07	.06	.03	.01	T	T	T	T				T	T				T	T	T			T	T		6
7		T	T	.01	.01	.03	.03	.02	.05	.05	.01	T								.02	T				7
8														T	T					.01	.09	T	T	T	8
9	.01	.01	.04	.05	.09	.11	.07	.03	.05	.05	.07	.05	.13	.07	.02	T	T	T	.01	T	.03	.05	.12	.10	9
10	.06	.10	.08	.08	.04	.03	.08	.03	.02	T	T	T	T	T			.01	.05	.04	.01	T	T	T	T	10
11				T	T						T	T			T	T	T							T	11
12	T	T					T	T		T	T	T	T	T											12
13							T	T																	13
14																									14
15																									15
16																									16
17																									17
18																									18
19																	T	T							19
20									T	T			T	T											20
21																									21
22																									22
23																									23
24				T	T	T	T	T	T	T	T	T	T	T	T	T	T	T							24
25																									25
26																									26
27																						.02	.04	.05	27
28	.04	.02	.04	.05	.04	.03	.01	.01	.04	.07	.11	.07	.04	T		T									28
29		T	T	T	T	T	T	T	T	.01	.01	T	T	T	T										29
30																									30
31								T	T									T	T					T	31

Data in columns 6, 12, 13, 14, and 15 are based on 8 observations per day at 3-hour intervals. Wind directions are those from which the wind blows. Resultant wind is the vector sum of wind directions and speeds divided by the number of observations. Figures for directions are tens of degrees from true North; i.e., 09 = East, 18 = South, 27 = West, 36 = North, and 00 = Calm. When directions are in tens of degrees in Col. 17, entries in Col. 16 are fastest observed 1-minute speeds. If the * appears in Col. 17, speeds are gusts. Any errors detected will be corrected and changes in summary data will be annotated in the annual Summary if published.

Subscription Price: Local Climatological Data $1.00 per year including annual Summary if published. Single copy 10 cents for monthly Summary, 15 cents for annual Summary. Checks or money orders should be made payable and remittances and correspondence should be sent to the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402.

I certify that this is an official publication of the Environmental Science Services Administration, and is compiled from records on file at the National Weather Records Center, Asheville, North Carolina 28801.

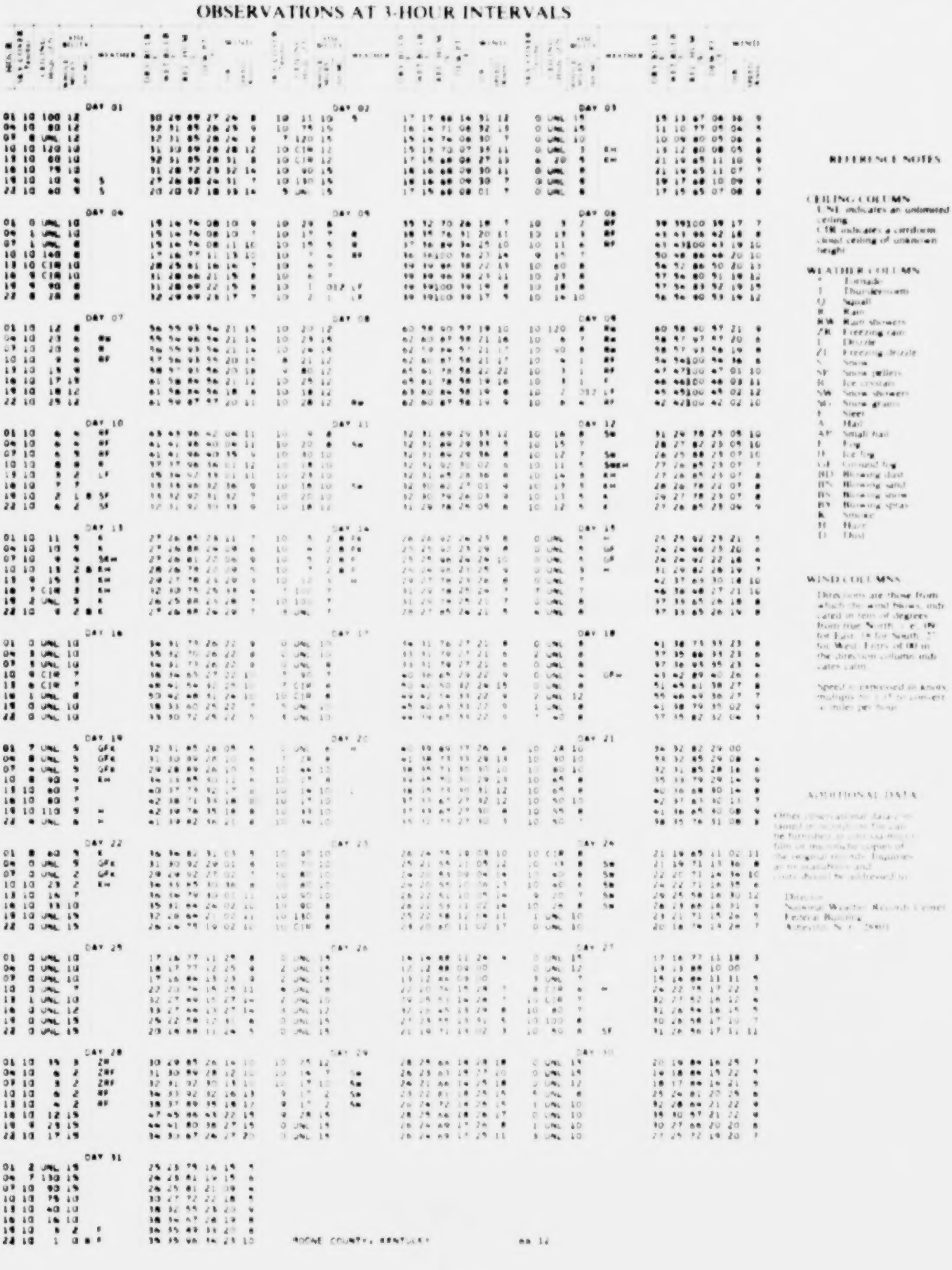
William H. Haggard
Director, National Weather Records Center

AVERAGES BY HOURS

								Resultant wind	
01	6	29.17	31	30	82	26	9.5	26	2.1
04	6	29.18	30	29	83	25	9.5	23	1.9
07	6	29.18	30	29	86	25	9.7	22	2.1
10	8	29.21	32	31	81	27	10.7	23	3.1
13	8	29.17	37	34	71	28	12.2	24	4.6
16	8	29.15	38	34	68	28	11.5	25	3.9
19	7	29.16	35	32	76	27	9.6	24	1.4
22	6	29.18	33	31	78	26	9.8	25	1.6

USCOMM ESSA ASHEVILLE 500

FIGURE 1



OBSERVATIONS AT 3-HOUR INTERVALS

REFERENCE NOTES

CEILING COLUMNS
UNL indicates an unlimited ceiling.
CIR indicates a cirroform cloud ceiling of unknown height.

WEATHER COLUMNS

+	Tornado
T	Thunderstorm
Q	Squall
R	Rain
RW	Rain showers
ZR	Freezing rain
L	Drizzle
ZL	Freezing drizzle
S	Snow
SP	Snow pellets
IC	Ice crystals
SW	Snow showers
SG	Snow grains
E	Sleet
A	Hail
AP	Small hail
F	Fog
IF	Ice fog
GF	Ground fog
BD	Blowing dust
BN	Blowing sand
BS	Blowing snow
BY	Blowing spray
K	Smoke
H	Haze
D	Dust

WIND COLUMNS

Directions are those from which the wind blows, indicated in tens of degrees from true North; i.e., 09 for East, 18 for South, 27 for West. Entry of 00 in the direction column indicates calm.

Speed is expressed in knots; multiply by 1.15 to convert to miles per hour.

ADDITIONAL DATA

Other observational data, contained in or on the original records, can be furnished at cost via microfilm or microfiche copies of the original records. Inquiries as to availability and costs should be addressed to:

Director
National Weather Records Center
Federal Building
Asheville, N.C. 28801

BOONE COUNTY, KENTUCKY

FIGURE 2

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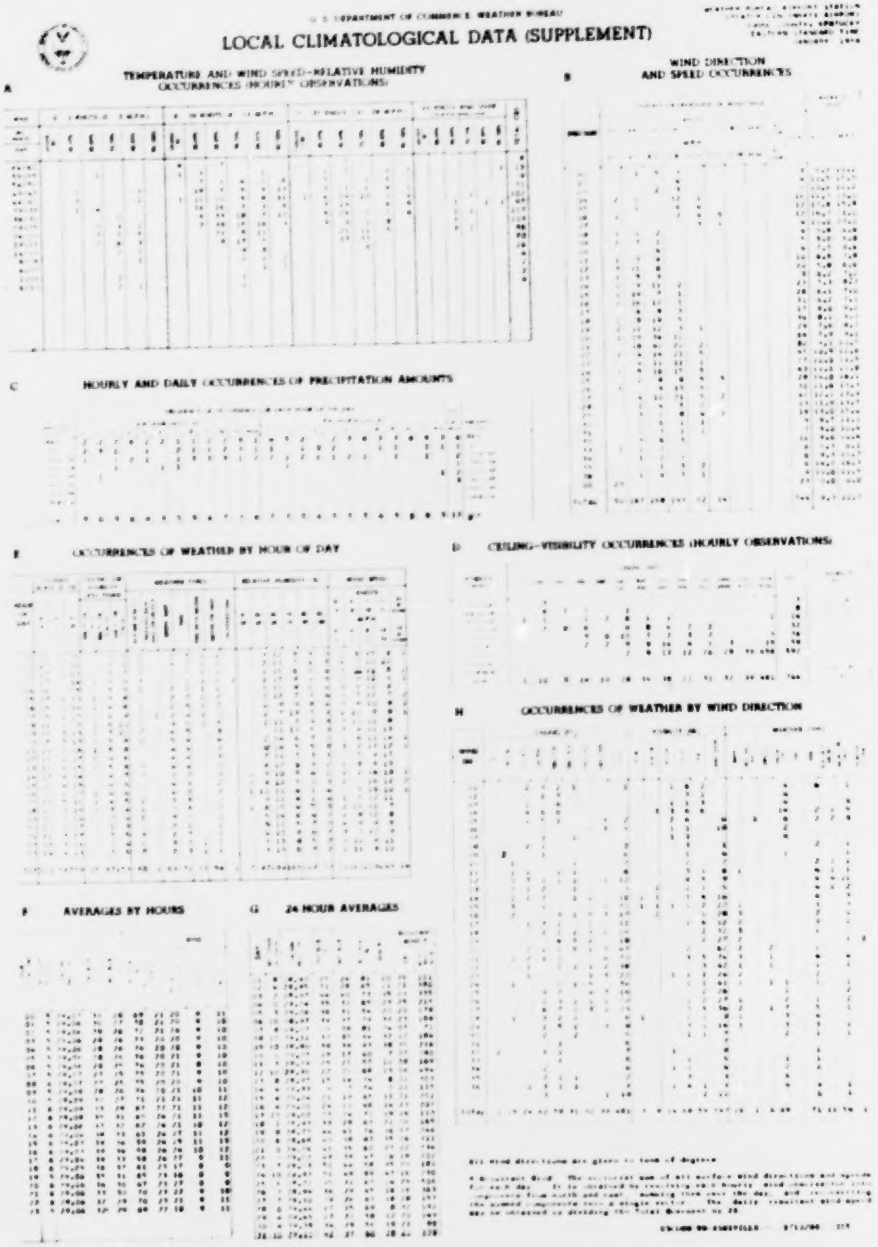


U.S. DEPARTMENT OF COMMERCE WEATHER BUREAU

LOCAL CLIMATOLOGICAL DATA (SUPPLEMENT)

A TEMPERATURE AND WIND SPEED-RELATIVE HUMIDITY OCCURRENCES (HOURLY OBSERVATIONS)

B WIND DIRECTION AND SPEED OCCURRENCES

C HOURLY AND DAILY OCCURRENCES OF PRECIPITATION AMOUNTS

E OCCURRENCES OF WEATHER BY HOUR OF DAY

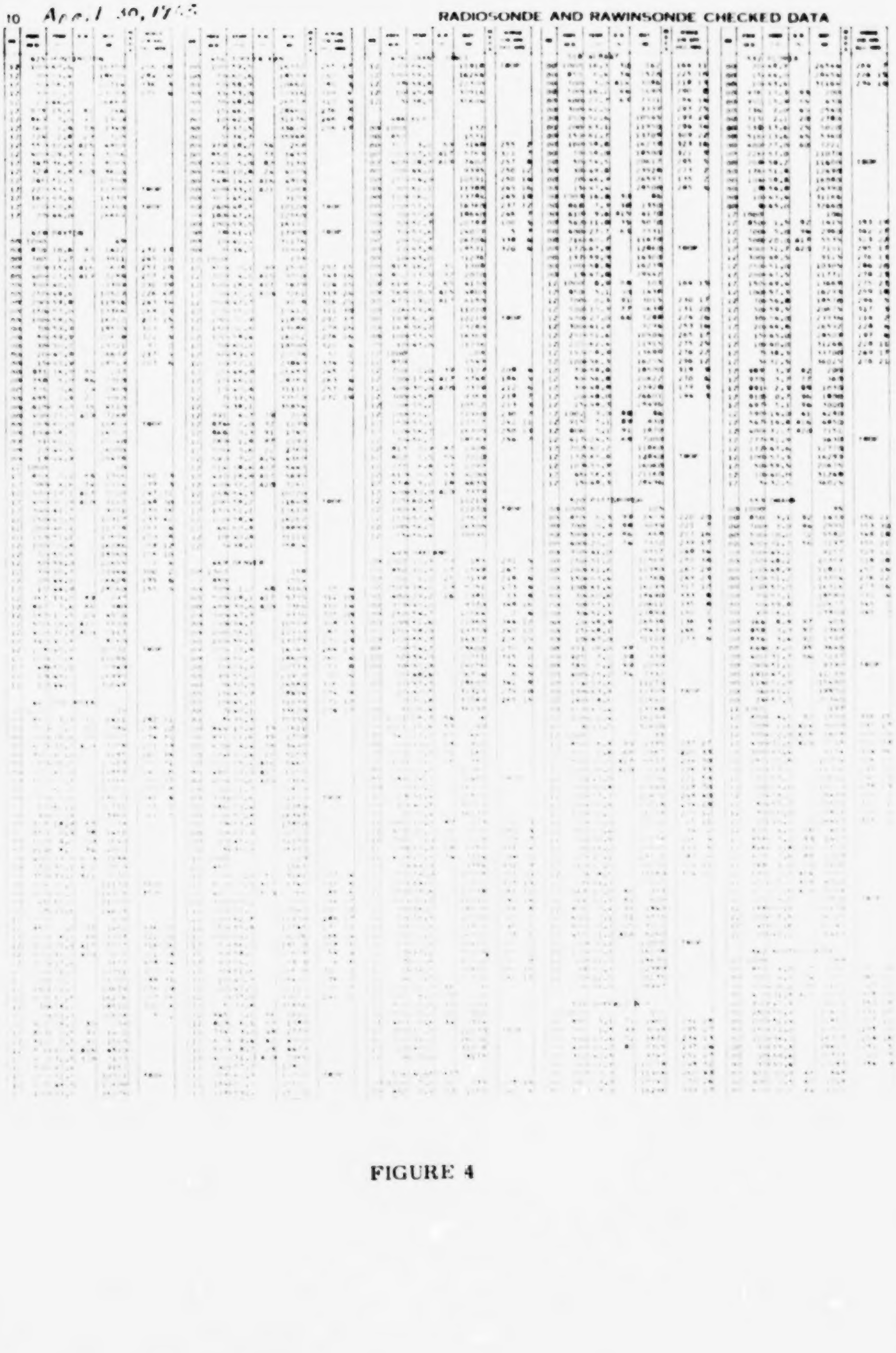
D CEILING-VISIBILITY OCCURRENCES (HOURLY OBSERVATIONS)

H OCCURRENCES OF WEATHER BY WIND DIRECTION

F AVERAGES BY HOURS

G 24 HOUR AVERAGES

FIGURE 3

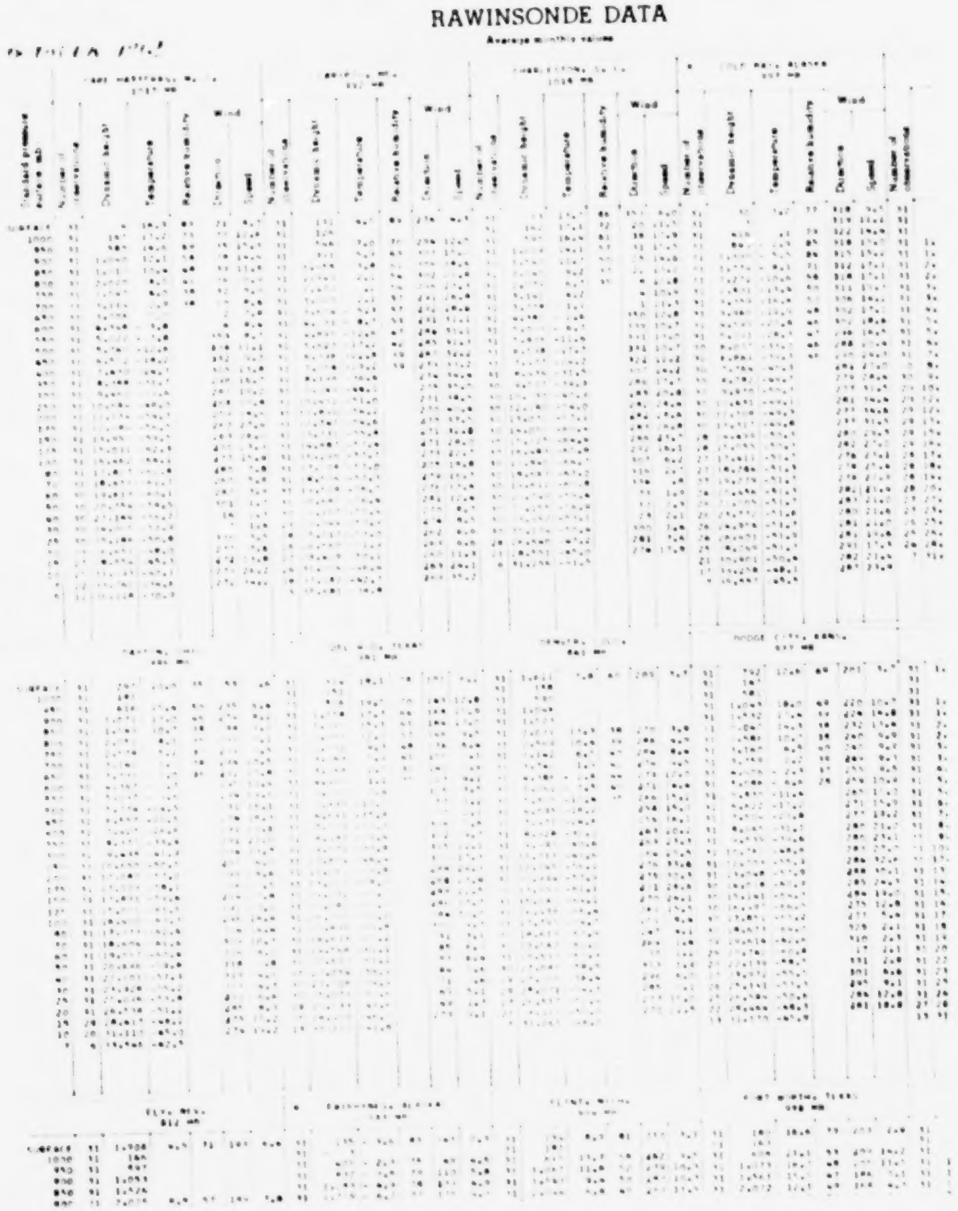


10 April 30, [illegible]

RADIOSONDE AND RAWINSONDE CHECKED DATA

FIGURE 4

Reproduced from best available copy.



RAWINSONDE DATA

Average monthly values

FIGURE 5

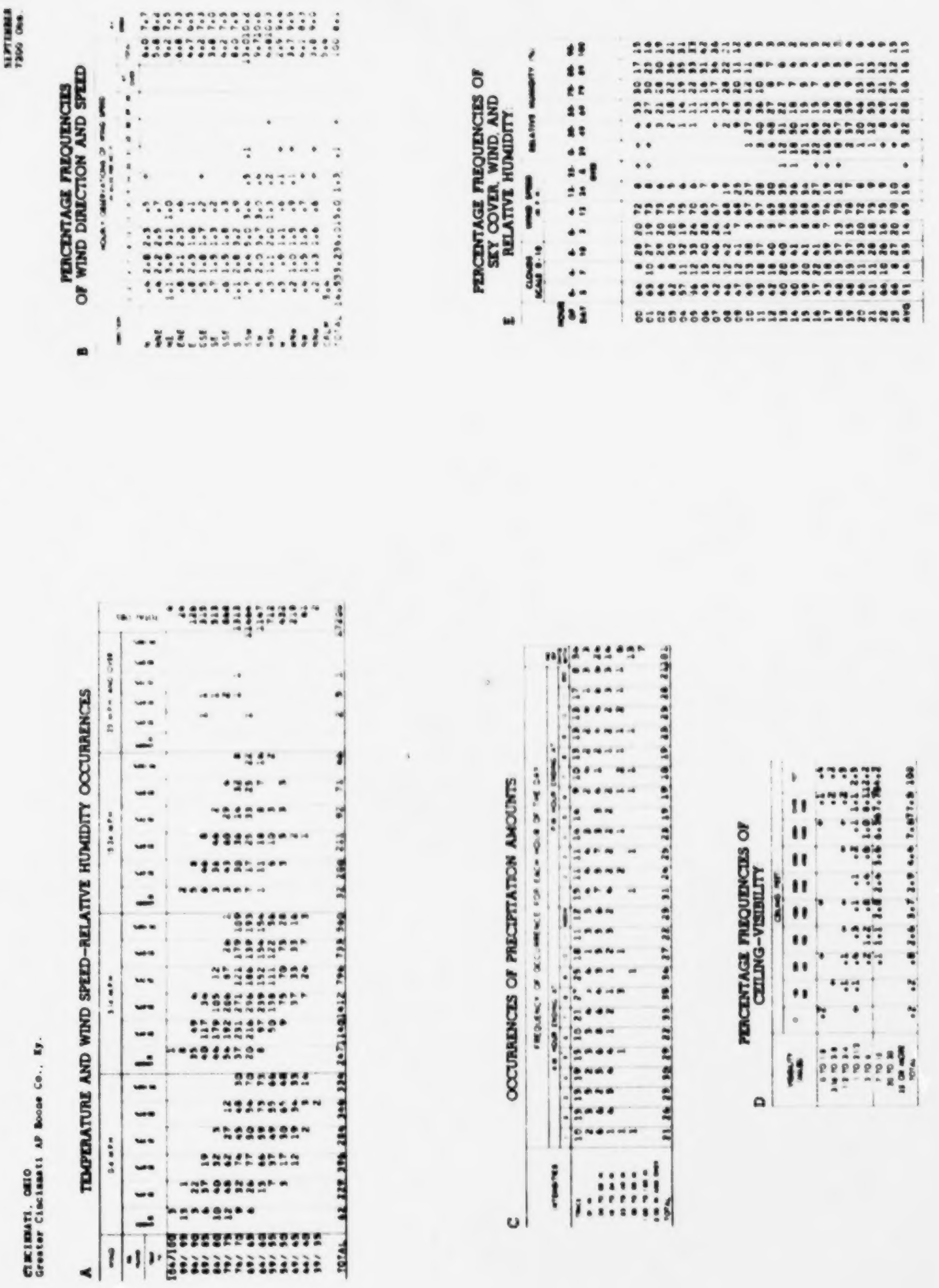
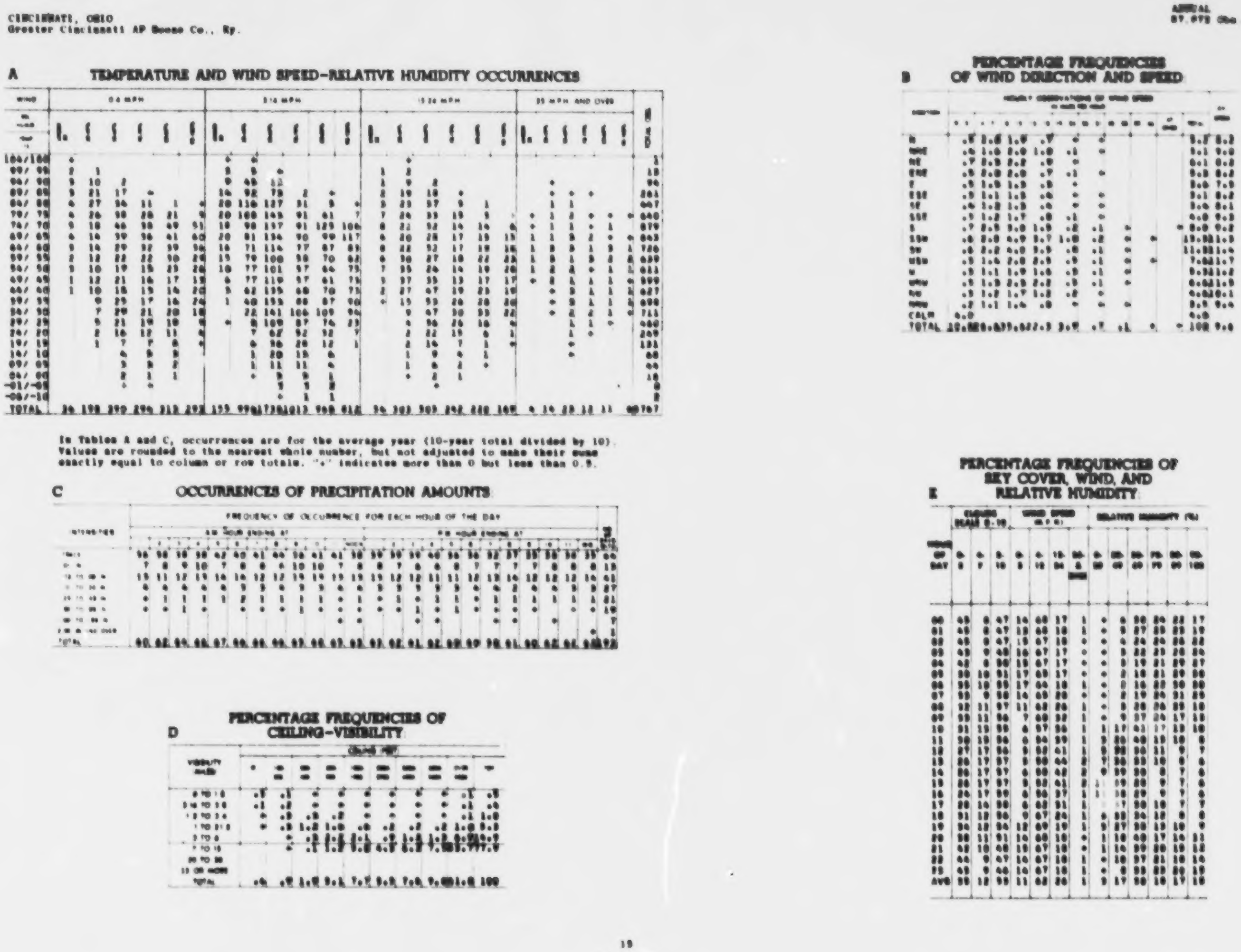

CINCINNATI, OHIO
Greater Cincinnati AP Boone Co., Ky.
A
TEMPERATURE AND WIND SPEED–RELATIVE HUMIDITY OCCURRENCES
B
PERCENTAGE FREQUENCIES OF WIND DIRECTION AND SPEED
SEPTEMBER
C
OCCURRENCES OF PRECIPITATION AMOUNTS
D
PERCENTAGE FREQUENCIES OF CEILING–VISIBILITY
E
PERCENTAGE FREQUENCIES OF SKY COVER, WIND, AND RELATIVE HUMIDITY
11

FIGURE 6



CINCINNATI, OHIO
Greater Cincinnati AP Boone Co., Ky.

ANNUAL

A TEMPERATURE AND WIND SPEED-RELATIVE HUMIDITY OCCURRENCES

In Tables A and C, occurrences are for the average year (10-year total divided by 10). Values are rounded to the nearest whole number, but not adjusted to make their sums exactly equal to column or row totals. "+" indicates more than 0 but less than 0.5.

C OCCURRENCES OF PRECIPITATION AMOUNTS

D PERCENTAGE FREQUENCIES OF CEILING-VISIBILITY

B PERCENTAGE FREQUENCIES OF WIND DIRECTION AND SPEED

E PERCENTAGE FREQUENCIES OF SKY COVER, WIND, AND RELATIVE HUMIDITY

19

FIGURE 7

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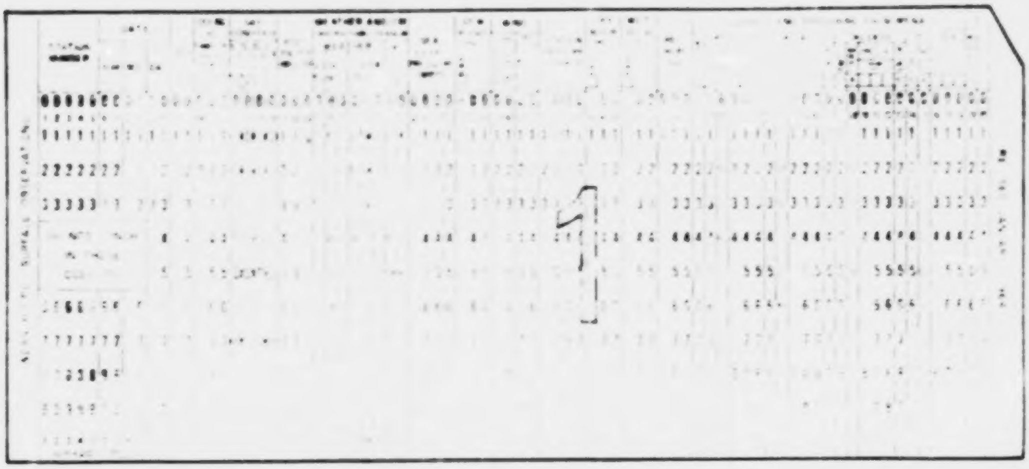

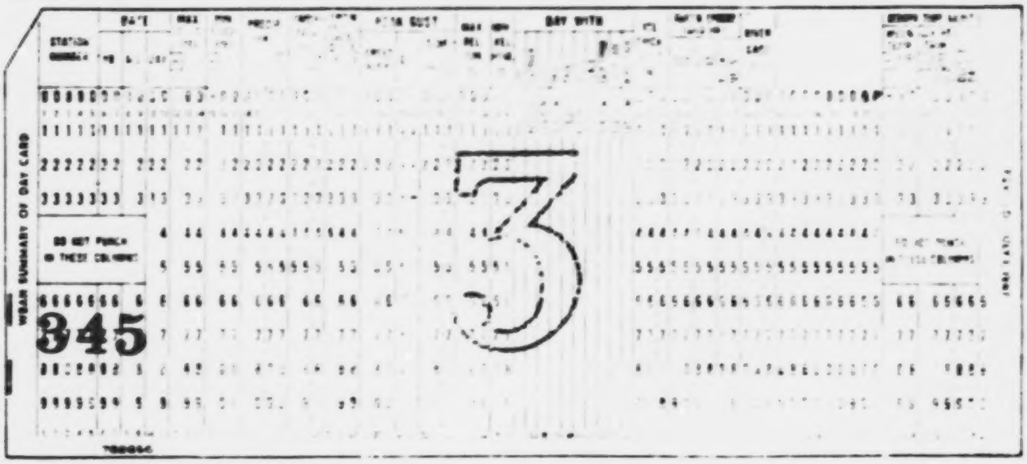
WBAN SUMMARY OF DAY CARD
STATION NUMBER
DATE
DAY WITH
DO NOT PUNCH IN THESE COLUMNS
345
3

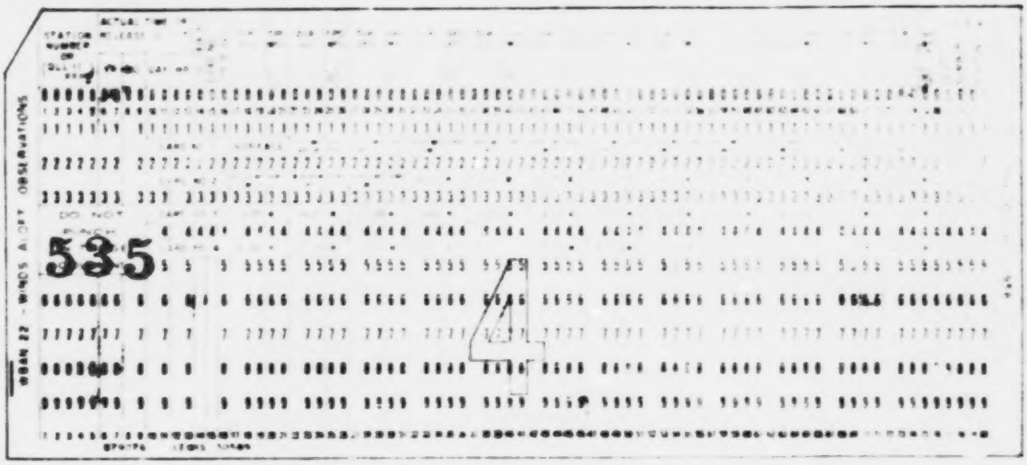
WBAN 22 - WINDS ALOFT OBSERVATIONS
STATION NUMBER
DO NOT PUNCH
535
4

FIGURE 8

Card number [illegible] not used after December 31, [illegible].

PART TWO

Climatography of the United States
Series No. 82

This series, Decennial Census of United States Climate - Summary of Hourly Observations, is incomplete, although work on it has been temporarily discontinued. It is generally based on ten years of data. Similar summaries, based on five years of record are contained in Climatography of the United States, Series No. 30.

It has been issued for the stations listed. The second part of the series number indicates the State in which the station presented is located; for example, all stations in New York State carry the number 82-30.

The list of numbers and stations is:

82-1 Alabama
Birmingham
Mobile
Montgomery

82-2 Arizona
Phoenix
*Tucson

82-3 Arkansas
Little Rock

82-4 California
*Bakersfield
Burbank
Fresno
Los Angeles
Oakland
Sacramento
San Diego
San Francisco

82-5 Colorado
*Colorado Springs
Denver

82-6 Connecticut
*Hartford

82-7 Delaware
Wilmington

82-8 Florida
Jacksonville
Miami
*Orlando
*Tallahassee
Tampa
*West Palm Beach

82-9 Georgia
Atlanta
Augusta
*Macon
Savannah

82-10 Idaho
Boise

82-11 Illinois
*Chicago (O'Hare)
Chicago (Midway)
Moline
Springfield

82-12 Indiana
Evansville
Fort Wayne
Indianapolis
*South Bend

82-13 Iowa
Des Moines
Sioux City

82-14 Kansas
Topeka
Wichita

82-15 Kentucky
*Lexington
Louisville

82-16 Louisiana
Baton Rouge
Lake Charles
New Orleans
Shreveport

82-17 Maine
Portland

82-18 Maryland
Baltimore

82-19 Massachusetts
Boston

82-20 Michigan
Detroit (City AP)
*Flint
Grand Rapids

82-21 Minnesota
Duluth
Minneapolis

82-22 Mississippi
Jackson

82-23 Missouri
Kansas City
St. Louis
Springfield

82-24 Montana
Great Falls

82-25 Nebraska
Omaha

82-26 Nevada
*Las Vegas
*Reno

82-28 New Jersey
Newark

82-29 New Mexico
Albuquerque

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*5 Year Summary Only

82-30 New York
Albany
*Binghamton
Buffalo
New York (Int'l)
New York (La Guardia)
Rochester
Syracuse

82-31 North Carolina
Charlotte
Greensboro
Raleigh
*Winston-Salem

82-32 North Dakota
Bismarck
Fargo

82-33 Ohio
Akron-Canton
Cincinnati
Cleveland
Columbus
Dayton
Youngstown

82-34 Oklahoma
Oklahoma City
Tulsa

82-35 Oregon
Medford
*Pendleton
Portland
*Salem
*Not Prepared

82-36 Pennsylvania
Harrisburg
Philadelphia
*Pittsburgh
*Scranton

82-37 Rhode Island
Providence

82-38 South Carolina
Charleston
Columbia

82-39 South Dakota
Huron
*Rapid City

82-40 Tennessee
Chattanooga
Knoxville
Memphis
Nashville

82-41 Texas
Amarillo
Austin
Brownsville
Corpus Christi
Dallas
El Paso
*Fort Worth
Galveston
Houston
Laredo
*Lubbock
*Midland
San Antonio
*Waco
*Witchita Falls

82-42 Utah
Salt Lake City

82-43 Vermont
*Burlington

82-44 Virginia
Norfolk
Richmond
*Roanoke

82-45 Washington
Seattle-Tacoma AP
Spokane

82-46 West Virginia
*Charleston

82-47 Wisconsin
*Green Bay
Madison
Milwaukee

82-48 Wyoming
*Casper

82-49 Alaska
*Anchorage
*Cold Bay
*Fairbanks
*King Salmon

82-50
Washington, D. C.

82-51 Hawaii
*Hilo
Honolulu
*Wake Island (Pacific)

82-52 Puerto Rico
San Juan

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*5 Year Summary Only

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ESSA Weather Bureau State Climatologist
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ESSA State Climatologist
Weather Bureau Office
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SECTION EIGHT

ASSISTANCE IN AIR POLLUTION METEOROLOGY

Assistance in Meteorologic Problems

ASSISTANCE IN METEOROLOGIC PROBLEMS

J.L. Dicke*

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Air Pollution Control Association
4400 Fifth Avenue,
Pittsburgh 13, Pennsylvania

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American Meteorological Society
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Washington 25, D.C.

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London, S.W. 7

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Office of Manpower Development, NAPCA

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PROFESSIONAL METEOROLOGICAL CONSULTANTS

Professional meteorologists advertise their services in the Professional Directory section of the Bulletin of the American Meteorological Society. In the Nov. 1970 Bulletin, 53 such firms and individuals were listed. The American Meteorological Society has in the last several years instituted a program of certifying consulting meteorologists. Of the 53 listings of professional services listed in the Bulletin, 27 are Certified Consulting Meteorologists. A total of 97 meteorologists had been certified as of March, 1970.

LOCAL U.S. WEATHER BUREAU OFFICE

A wealth of meteorological information and experience is available at the local city or airport Weather Service Office pertaining to local climatology, pecularities in local micrometeorological conditions including topographic effects, and exposure and operating characteristics of meteorological instruments. The Air

Pollution Potential Advisories are received here by teletype from the National Meteorological Center. Often the public telephones the Weather Service with air pollution complaints which the meteorologists may have traced back to a specific source by examining local wind circulations. Through personal contact with the meteorologist-in-charge (MIC) specific, localized forecasts may be arranged to support a short-term air pollution investigation or sampling program.

CONTRACT WORK

Many universities do contract work for private organizations and for government agencies on meteorological problems and also on air pollution surveys.

SOURCES OF AIR POLLUTION LITERATURE

Publications Abstracting Air Pollution Literature

1 Air Pollution Abatement Manual
Manufacturing Chemists' Association, Inc.
1625 Eye Street, N. W.
Washington 6, D. C.

2 The Air Pollution Bibliography
The Library of Congress
Technical Information Division
Washington, D. C.

3 Air Pollution Control Association Abstracts
Air Pollution Control Association
4400 Fifth Avenue
Pittsburgh 13, Pennsylvania

4 Applied Science and Technology Index
The H. W. Wilson Company
950 University Avenue
New York 52, New York

5 Battelle Technical Review
Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio

6 Chemical Abstracts
American Chemical Society
1155 Sixteenth Street, N. W.
Washington 6, D. C.

7 Engineering Index
Engineering Index, Inc.
345 East 47th Street
New York 17, New York

8 Environmental Effects on Materials and Equipment
Prevention of Deterioration Center
National Academy of Sciences
National Research Council
2101 Constitution Avenue, N. W.
Washington 15, D. C.

9 Meteorological and Geoastrophysical Abstracts
American Meteorological Society
45 Beacon Street
Boston 8, Massachusetts

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Superintendent of Documents
U. S. Government Printing Office
Washington 25, D. C.

11 Public Health Engineering Abstracts
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U. S. Government Printing Office
Washington 25, D. C.

12 Quarterly Cumulative Index Medicus
American Medical Association
535 N. Dearborn Street
Chicago 10, Illinois

13 Readers' Guide to Periodical Literature
The H. W. Wilson Company
950 University Avenue
New York 52, New York

14 Clearinghouse Announcements in Science and Technology
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Pub. twice monthly. $5 per year.
CFSTI U.S. Dept. Commerce
Springfield, Va. 22151

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1 Air Engineering
Business News Publishing Company
450 W. Fort Street
Detroit 26, Michigan

2 American City
The American City Magazine Corporation
470 Fourth Avenue,
New York 16, New York

3 American Industrial Hygiene Association Journal
14125 Prevost
Detroit 27, Michigan

4 American Journal of Public Health and Nations' Health
American Public Health Association, Inc.
1790 Broadway
New York 19, New York

5 Archives of Environmental Health
American Medical Association
535 N. Dearborn Street
Chicago 10, Illinois

6 Atmospheric Environment
Pergamon Press
122 East 55th Street
New York 22, New York

7 Atmospheric Pollution Bulletin
Warren Spring Laboratory
Gunnels Wood Road
Stevenage, England

8 Chemical Engineering
McGraw-Hill Publishing Company, Inc.
330 W. 42nd Street
New York 36, New York

9 Chemical Engineering Progress
American Institute of Chemical Engineers
345 47th Street
New York 17, New York

10 Chemical Reviews
American Chemical Society
20th and Northampton Streets
Easton, Pennsylvania

11 Environmental Health Series
National Center for Air Pollution Control
4676 Columbia Parkway
Cincinnati, Ohio 45226

12 Heating, Piping and Air Conditioning
Keeney Publishing Company
6 North Michigan Avenue
Chicago 2, Illinois

13 Industrial and Engineering Chemistry
American Chemical Society
1155 Sixteenth Street, N. W.
Washington 6, D. C.

14 Industrial Hygiene Foundation of America, Transactions Bulletin
Industrial Hygiene Foundation of American, Inc.
4400 Fifth Avenue
Pittsburgh 13, Pennsylvania

15 Industrial Medicine and Surgery
Industrial Medicine Publishing Company
P. O. Box 306
Miami, Florida 33144

16 Industrial Water and Wastes
Scranton Publishing Company, Inc.
35 E. Wacker Drive
Chicago, Illinois

17 Journal of the Air Pollution Control Association
Air Pollution Control Association
4400 Fifth Avenue
Pittsburgh 13, Pennsylvania

18 Journal of Colloid Science
Academic Press, Inc.
111 Fifth Avenue
New York 3, New York

19 Mechanical Engineering
American Society of Mechanical Engineers
345 E. 47th Street
New York 17, New York

20 The Oil and Gas Journal
211 South Cheyenne Avenue
Tulsa 3, Oklahoma

21 Public Health Reports
U. S. Department of Health, Education, and Welfare
Public Health Service, Superintendent of Documents
U. S. Government Printing Office
Washington, D. C. 20402

22 Public Works
Public Works Journal Corporation
200 South Broad Street
Ridgewood, New Jersey

23 Smokeless Air
National Society for Clean Air
Field House, Breams Building
London E. C. 4, England

24 Transactions of the American Society of Mechanical Engineers
Journal of Engineering for Power (Series A of the Transactions of the ASME)
Journal of Engineering for Industry (Series B)
Journal of Heat Transfer (Series C)
Journal of Basic Engineering (Series D)
Journal of Applied Mechanics (Series E)
American Society of Mechanical Engineers
345 East 47th Street
New York 17, New York

25 Transactions of Institution of Chemical Engineers
Institution of Chemical Engineers
16 Belgrave Square
London S. W. 1, England

26 Environmental Science and Technology
American Chemical Society
1155 Sixteenth Street N. W.
Washington, D. C. 20036

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APPENDIX

Glossary
Elementary Statistical Description of Data
Index
Units of Measure for Dimensional Systems
Values and Logarithms of Exponential Functions
Conversion Factors
    Temperature, Pressure
    Length, Area
    Volume, Flow
    Weight, Concentration
    Velocity, Emission Rates
    International Atomic Weights

GLOSSARY

Most of the definitions of the following terms are taken from the "Glossary of Meteorology" (1959).

actinometer - The general name for any instrument used to measure the intensity of radiant energy, particularly that of the sun.

adiabatic process - A thermodynamic change of state of a system in which there is no transfer of heat or mass across the boundaries of the system.

advection - The process of transport of an atmospheric property solely by the mass motion (velocity field) of the atmosphere. The description of predominantly horizontal large scale motions of the atmosphere.

aerometric - Pertaining to the science of measuring properties of the air.

air drainage - General term for gravity-induced, downslope flow of relatively cold air. Winds thus produced are called gravity winds.

air mass - A widespread body of air, the properties of which can be identified as a) having been established while that air was situated over a particular region of the earth's surface (air-mass source region), and b) undergoing specific modifications while in transit away from the source region. An air mass is often defined as a widespread body of air that is approximately homogeneous in its horizontal extent, particularly with reference to temperature and moisture distribution; in addition, the vertical temperature and moisture variations are approximately the same over its horizontal extent. The stagnation or long-continued motion of air over a source region permits the vertical temperature and moisture distribution of the air to reach relative equilibrium with the underlying surface.

air pollution - The presence, in the ambient atmosphere, of substances put there by the activities of man in concentrations sufficient to interfere directly or indirectly with his health, safety, or comfort, or with the full use and enjoyment of his property.

air pollution meteorology - The study of atmospheric phenomena that influence or are influenced by air pollutants.

albedo - The ratio of the amount of electromagnetic radiation reflected by a body to the amount incident upon it, commonly expressed as a percentage. The albedo is to be distinguished from the reflectivity, which refers to one specific wavelength (monochromatic radiation).

anemometer - The general name for instruments designed to measure the speed (or force) of the wind.

anticyclone - An atmospheric anticyclonic circulation (clockwise in the northern hemisphere), a closed circulation. With respect to the relative direction of its rotation, it is the opposite of a cyclone. Because anticyclonic circulation and relative high atmospheric pressure usually coexist, the terms anticyclone and high are used interchangeably in common practice.

backing - 1) According to general internationally accepted usage, a change in wind direction in a counterclockwise sense (e.g. south to southeast to east) in either hemisphere of the earth; the opposite of veering.

2) According to widespread usage among U. S. meteorologists, a change of wind direction in a counterclockwise sense in the northern hemisphere, clockwise in the southern hemisphere.

Beaufort wind scale - A system of estimating and reporting wind speeds, invented in the early nineteenth century by Admiral Beaufort of the British Navy. It was originally based on the effects of various wind speeds on the amount of canvas that a full-rigged frigate of the period could carry, but has since been modified and modernized.

bivane - A bi-directional wind vane, a sensitive wind vane used in turbulence studies to obtain a record of the horizontal and vertical components of the wind. The instrument consists of two lightweight air-foil sections mounted orthogonally on the end of a counter-balanced rod which is free to rotate in the horizontal and vertical planes. The positions of the rod may be recorded by electrical techniques.

bridled-cup anemometer - A combination cup anemometer and pressure-plate anemometer, consisting of an array of cups about a vertical axis of rotation, the free rotation of which is restricted by a suitable spring arrangement. By proper adjustment of the force constant of the spring, it is possible to obtain an angular displacement which is proportional to wind velocity. A bridled-cup anemometer is frequently used to measure high wind speeds.

buoyancy - That property of an object that enables it to ascend through or remain freely suspended in a compressible fluid such as the atmosphere. Quantitatively, the ratio of the specific weights of the fluid and the object.

calm - The absence of apparent motion of the air.

Campbell-Stokes recorder - A sunshine recorder which consists of a spherical lens which burns an image of the sun upon a specially prepared card. The depth and breadth of the trace may be interpreted in terms of intensity of the sun.

cascade impactor - A low speed impaction device for use in sampling both solid and liquid atmospheric suspensoids. Four pairs of jets and sampling plates work in series and are designed so that each collects particles in one size range.

climate - "The synthesis of the weather"; the long-term manifestations of weather, however they may be expressed. More rigorously, the climate of a specified area is represented by the statistical collective of its weather conditions during a specified interval of time (usually several decades).

climatology - The scientific study of climate. In addition to the presentation of climatic data, it includes the analysis of the causes of differences of climate, and the application of climatic data to the solution of specific design or operational problems.

condensation nucleus - A particle, either liquid or solid, upon which condensation of water vapor begins in the atmosphere.

convection - As specialized in meteorology, atmospheric motions that are predominantly vertical, resulting in vertical transport and mixing of atmospheric properties.

coriolis force - A force per unit mass on moving particles arising solely from the earth's rotation. It acts as a deflecting force, normal to the velocity, to the right of motion in the northern hemisphere and to the left in the southern hemisphere.

dew point - (or dew point temperature) - The temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content in order for saturation to occur.

diffusion - In meteorology, the exchange of fluid parcels (and hence the transport of conservative properties) between regions in space, in the apparently random motions of a scale too small to be treated by the equations of motion.

Dines anemometer - A pressure-tube anemometer in which the pressure head on the windward end of a weather vane is kept facing into the wind. Another head develops suction independent of wind direction. The pressure difference between the two heads is proportional to wind speed squared and is measured by a float manometer.

direct solar radiation - That portion of the radiant energy received at an instrument direct from the sun as opposed to diffuse sky radiation or radiation from any other source.

dispersion - The process by which radiation is separated into its component wavelengths. Dispersion results when an optical process such as diffraction, refraction, or scattering varies according to wavelength.

diurnal - Daily, especially pertaining to actions which are completed within twenty-four hours and which recur every twenty-four hours; thus, most reference is made to diurnal cycles, variations, ranges, etc.

downwind - The direction toward which the wind is blowing; with the wind.

dry-adiabatic lapse rate - A special process lapse rate of temperature, defined as the rate of decrease of temperature with height of a parcel of dry air lifted adiabatically through an atmosphere in hydrostatic equilibrium, numerically equal to 9.767°C per km., or 5.4°F per thousand feet.

eddy - 1) By analogy with a molecule, a "glob" of fluid within the fluid mass that has a certain integrity and life history of its own; the activities of the bulk fluid being the net result of the motion of the eddies.

2) Any circulation drawing its energy from a flow of much larger scale, and brought about by pressure irregularities as in the lee of a solid obstacle.

eddy diffusion - (or turbulent diffusion) - The diffusion of a conservative property by eddies in a turbulent flow.

Ekman layer - (sometimes called spiral layer) - The layer of transition between the surface boundary, where the shearing stress is constant, and the free atmosphere where the atmosphere is treated as an ideal fluid in approximate geostrophic equilibrium.

Eulerian coordinates - Any system of coordinates in which properties of a fluid are assigned to fixed points in space at a given time without attempting to identify individual parcels from one time to the next.

exchange coefficients - Coefficients of eddy flux in turbulent flow. The hypothesis states that the mean eddy flux per unit area of a conservative quantity is proportional to the gradient of the mean value of the quantity.

free atmosphere - (sometimes called free air) - That portion of the earth's atmosphere, above the planetary boundary layer, in which the effect of the earth's surface friction on the air motion is negligible, and in which the air is usually treated (dynamically) as an ideal fluid. The base of the free atmosphere is usually taken as the geostrophic wind level.

friction layer - 1) Same as planetary boundary layer.

2) Same as surface boundary layer.

geostrophic wind - That horizontal wind velocity for which the coriolis acceleration exactly balances the horizontal pressure force. The geostrophic wind is thus directed along the contour lines on a constant pressure surface (or along the isobars in a geopotential surface) with low elevations (or low pressure) to the left in the northern hemisphere and to the right in the southern hemisphere.

greenhouse effect - The heating effect exerted by the atmosphere upon the earth by virtue of the fact that the atmosphere (mainly, its water vapor) absorbs and remits infrared radiation. In detail: the shorter wavelengths of isolation are transmitted rather freely through the atmosphere to be absorbed at the earth's surface. The earth then re-emits this long-wave (infrared) terrestrial radiation, a portion of which is absorbed by the atmosphere and again emitted. Some of this is emitted downward back to the earth's surfact. It is essential, in understanding the concept of the greenhouse effect, to note that the important additional warming is due to the counter-radiation from the atmosphere. The glass panes of a greenhouse function in this manner exactly analogously to the atmosphere in maintaining high greenhouse temperatures, hence the name.

gust - A sudden brief increase in the speed of the wind. According to the U. S. weather observing practice, gusts are reported when the peak wind speed reaches at least 16 knots and the variation in wind speed between the peaks and lulls is at least 9 knots. The duration of a gust is usually less than 20 seconds.

haze - Fine dust or salt particles dispersed through a portion of the atmosphere, a type of lithometeor. The particles are so small they cannot be felt or individually seen by the naked eye.

hot-wire anemometer - An anemometer which utilizes the principle that the convection of heat from a body is a function of ventilation. Wind speed is determined by measuring either the current required to maintain the hot wire at a constant temperature or the resistance variation while a constant current is maintained.

illuminometer - Same as photometer.

instability - A property of the steady state of a system such that certain disturbances or perturbations introduced into the steady state will increase in magnitude.

inversion - A departure from the usual decrease or increase with altitude of the value of an atmospheric property, also, the layer through which this departure occurs.

inversion, temperature - A layer in which temperature increases with altitude. The principal characteristic of an inversion layer is its marked static stability, so that very little turbulent exchange can occur within it. Strong wind shears often occur across inversion layers, and abrupt changes in concentrations of atmospheric particulates and atmospheric water vapor may be encountered on ascending through the inversion.

isokinetic sampling - A technique for collecting airborne particulate matter in which the airstream entering the collector has a velocity equal to the air passing around and outside the collector.

kytoon - A captive balloon used to maintain meteorological equipment aloft at an approximately constant height. It is streamlined and combines the aerodynamic properties of a balloon and a kite.

lapse rate - The decrease of atmospheric temperature with height. The term applies ambiguously to the environmental lapse-rate and the process lapse-rate, and the meaning must often be ascertained from the context.

lapse rate, environmental - The rate of decrease of temperature with elevation. The environmental lapse rate is determined by the distribution of temperature in the vertical at a given time and place and should be carefully distinguished from the process lapse rate, which applies to an individual air parcel.

lapse rate, process - The rate of decrease of temperature of an air parcel as it is lifted. In the atmosphere the process lapse rate is usually assumed to be either the dry-adiabatic lapse rate or the saturation-adiabatic lapse rate.

mesometeorology - That portion of the science of meteorology concerned with the study of atmospheric phenomena on a scale larger than that of micrometeorology, but smaller than the cyclonic scale.

meteorology - The study dealing with the phenomena of the atmosphere. This includes not only the physics, chemistry, and dynamics of the atmosphere, but is extended to include many of the direct effects of the atmosphere upon the earth's surface, the oceans, and life in general. The goals often ascribed to meteorology are the complete understanding, accurate prediction, and artificial control of atmospheric phenomena.

micrometeorology - That portion of the science of meteorology that deals with the observation and explanation of the smallest-scale physical and dynamic occurrences within the atmosphere. So far, studies in this field are confined to the surface boundary layer of the atmosphere; that is, from the earth's surface to an altitude where the effects of the immediate underlying surface upon air motion and composition become negligible. To date, the bulk of the work in this field has centered around the evaluation of low level atmospheric turbulence, diffusion, and heat transfer.

Mie Theory - A mathematical-physical theory of scattering of electromagnetic radiation which is not restricted to scattering by particles small compared to the wavelength of the scattered radiation but is valid for all ratios of diameter to wavelength.

mixing length - A mean length of travel characteristic of a particular motion over which an eddy maintains its identity; analogous to the mean free path of a molecule.

photometer - (also called illuminometer) - An instrument for measuring the intensity of light or the relative intensity of a pair of lights. If the instrument is designed to measure the intensity of light as a function of wavelength, it is called a spectro-photometer. Photometers may be divided into two classes: photoelectric photometers in which a photoelectric cell is used to compare electrically the intensity of an unknown light with that of a standard light, and visual photometers in which the human eye performs the function of a photo cell. A photometer used to measure the intensity of a distant light is referred to as a telephotometer or transmissometer.

planetary boundary layer - (also called friction layer, atmospheric boundary layer) - That layer of the atmosphere from the earth's surface to the geostrophic wind level including, therefore, the surface boundary layer and the Ekman layer. Above this layer lies the free atmosphere.

potential temperature - The temperature a parcel of dry air would have if brought adiabatically from its initial state to the standard pressure of 1000 mb.

prevailing wind - The wind direction most frequently observed during a given period.

pyrheliometer - General term for the class of actinometers which measure the intensity of direct solar radiation.

radiational cooling - The cooling of the earth's surface and adjacent air, accomplished whenever the earth suffers a net loss of heat due to terrestrial radiation.

radiosonde - A balloon borne instrument for the simultaneous measurement and transmission of meteorological data. The instrument consists of transducers for the measurement of pressure, temperature and humidity; a modulator for the conversion of the output of the transducers to a quantity which controls a property of the radio frequency signal; a selector switch which determines the sequence in which the parameters are to be transmitted; and a transmitter which generates the radio-frequency carrier.

Rayleigh scattering - Any scattering process produced by spherical particles whose radii are smaller than about one-tenth the wavelength of the scattered radiation. The scattering coefficient varies inversely with the fourth power of the wavelength.

relative humidity - The dimensionless ratio of the actual vapor pressure of the air to the saturation vapor pressure.

resultant wind - In climatology, the vectorial average of all wind directions and speeds for a given level at a given place for a certain period, as a month.

saturation-adiabatic lapse rate - A special case of process lapse rate, defined as the rate of decrease of temperature with height of an air parcel lifted in a saturation adiabatic process through an atmosphere in hydrostatic equilibrium. Owing to the release of latent heat, this lapse rate is less than the dry adiabatic lapse rate.

shear, wind - The local variation of the wind vector or any of its components in a given direction.

streak line - A line within a fluid which, at a given instant, is formed by those fluid particles which at some previous instant have passed through a specified fixed point in the fluid.

streamlines - A line whose tangent at any point in a fluid is parallel to the instantaneous velocity of the fluid at that point.

subsidence - A descending motion of air in the atmosphere, usually with the implication that the condition extends over a rather broad area.

surface boundary layer - (Also called surface layer, friction layer, atmospheric boundary layer, ground layer.) - That thin layer of air adjacent to the earth's surface extending up to the so-called anemometer level (the base of the Ekman layer). Within this layer the wind distribution is determined largely by the vertical temperature gradient and the nature and contours of the underlying surface, and shearing stresses are approximately constant.

synoptic - In meteorology, this term has become somewhat specialized in referring to the use of meteorological data obtained simultaneously over a wide area for the purpose of presenting a comprehensive and nearly instantaneous picture of the state of the atmosphere.

trajectory - A curve in space tracing the points successively occupied by a particle in motion. (a path).

turbulence - A state of fluid flow in which the instantaneous velocities exhibit irregular and apparently random fluctuations so that in practice only statistical properties can be recognized and subjected to analysis.

The satisfactory treatment of this phenomena in the atmosphere is perhaps the outstanding unsolved problem of theoretical meteorology.

valley breeze - A wind which ascends a mountain valley (up-valley wind) during the day, the daytime component of a mountain and valley wind system.

veering - 1) According to general international usage, a change in wind direction in a clockwise sense (e.g., south to southwest to west) in either hemisphere of the earth, the opposite of backing.

2) According to widespread usage among U.S. meteorologists, a change in wind direction in a clockwise sense in the northern hemisphere, counterclockwise in the southern hemisphere.

wind rose - Any one of a class of diagrams designed to show the distribution of wind direction experienced at a given location over a considerable period. The most common form consists of a circle from which sixteen lines emanate, one for each compass point. The length of each line is proportional to the frequency of wind from that direction, and the frequency of calm conditions is entered in the center.

wind vane - An instrument used to indicate wind direction.

wiresonde - An atmospheric sounding instrument which is supported by a captive balloon and used to obtain temperature and humidity data from the ground level to a height of a few thousand feet. Height is determined by means of a sensitive altimeter, or from the amount of cable released and the angle which the cable makes with the ground. The information is telemetered to the ground through a wire cable.

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ELEMENTARY STATISTICAL DESCRIPTION OF DATA

I DESCRIPTION OF DATA

Certain terms are used to describe data obtained in a study.

A Mean

The sum of all the observations divided by the number of observations is the mean.

$$\bar{X} = \frac{\Sigma X_i}{N} \qquad (1)$$

where:

$\bar{X}$ = mean of the observations

X_i = value of an individual observation

N = number of observations

B Geometric Mean

The Nth root of the product of all the observations is the geometric mean.

$$\bar{X}_g = \sqrt[N]{(X_1)\,(X_2)\ldots(X_N)} \qquad (2)$$

or:

$$\text{Log } \bar{X}_g = \frac{1}{N}\,\Sigma \log X_i \qquad (3)$$

where:

$\bar{X}_g$ = geometric mean

C Median

The median is the middle value of any group of observations. If the data are arranged from smallest to largest value, the median is the $\frac{N+1}{2}$ th term. It can be said of the median that 50% of the data are equal to or greater than its value; 50% are equal to or less than this value.

D Range

The range is the difference between the smallest and largest observations of a series.

E Variance

The variance is defined as the sum of the squares of the deviations of the observations from their mean, divided by one less than the total number of observations.

$$s^2 = \frac{\Sigma (X_i - \bar{X})^2}{N - 1} \qquad (4)$$

where:

s^2 = variance

An equivalent formula for s^2 which is simpler to use for computations is:

$$s^2 = \frac{\Sigma X_i^2 - \frac{(\Sigma X_i)^2}{N}}{N - 1} \qquad (5)$$

F Standard Deviation

The standard deviation is defined as the positive square root of the variance.

$$s = \sqrt{\frac{\Sigma (X_i - \bar{X})^2}{N - 1}} \qquad (6)$$

where:

s = standard deviation or, from equation (5):

$$s = \sqrt{\frac{\Sigma X_i^2 - \frac{(\Sigma X_i)^2}{N}}{N - 1}} \qquad (7)$$

Note: The variance and standard deviation are meaningful measures of variation only if the data are normally distributed.

G Correlation Coefficient

The correlation coefficient is a measure of the linear dependence between two variables. By mathematical definition the correlation coefficient can vary in magnitude from -1 to + 1.

The equation of the correlation coefficient is given by:

$$r = \frac{N\Sigma X_iY_i - \Sigma X_i \Sigma Y_i}{\sqrt{\left[N\Sigma X_i^2 - (\Sigma X_i)^2\right]\left[N\Sigma Y_i^2 - (\Sigma Y_i)^2\right]}}$$

where:

r = correlation coefficient

ΣX_i = sum of measurements of first variable

ΣY_i = sum of measurements of second variable

N = number of measurements

H Linear Regression Line

If the relation between two variable is significant, a further test is whether the data can be represented by a straight line in the form $y = a + bx$. To solve for the constants a and b the equations are:

$$a = \frac{\Sigma X_i^2 \Sigma Y_i - \Sigma X_i \Sigma X_iY_i}{N\Sigma X_i^2 - (\Sigma X_i)^2}$$

and:

$$b = \frac{N\Sigma X_iY_i - \Sigma X_i\Sigma Y_i}{N\Sigma X_i^2 - (\Sigma X_i)^2}$$

where:

b = slope of regression line

a = intercept of regression line

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DIMENSIONAL SYSTEMS AND SELECTED SYSTEMS OF UNITS OF MEASUREMENT

Table 1. Common Systems of Units of Measurement for the Various Dimensional Systems

Item	Symbol	Definition	Dimensions			MASS - LENGTH - TIME Metric $\frac{cm - gm_m}{sec - °K}$	$\frac{cm\text{-}gm_m}{dyne\text{-}sec^2 - °K}$
acceleration	a		$\frac{length}{(time)^2}$			$\frac{cm}{sec^2}$	$\frac{cm}{sec^2}$
force	F		force $\frac{(mass)(length)}{(time)^2}$			$\frac{gm_m - cm}{sec^2}$	dyne
local acceleration due to gravity	g		$\frac{length}{(time)^2}$			$\frac{cm}{sec^2}$	$\frac{cm}{sec^2}$
dimensional constant	g_c		variable			(1) dimensionless	$(1)\frac{gm_m\text{-}cm}{dyne\text{-}sec^2}$
mass	m		$\frac{(force)(time)^2}{(length)}$ mass			gm_m	gm_m
density	ρ	$\frac{mass}{volume}$	$\frac{(force)(time)^2}{(length)^4}$ $\frac{mass}{(length)^3}$			$\frac{gm_m}{cm^3}$	$\frac{gm_m}{cm^3}$
universal gas constant	R	$\frac{(force)(length)}{(mass\text{-}mole)(temp)}$	$\frac{(mass)(length)^2}{(time)^2(mass\text{-}mole)(temp)}$	$\frac{(force)(length)}{\left[\frac{(force)(time)^2}{(length)} - mole\right](temp)}$	$\frac{(force)(length)}{(mass\text{-}mole)(temp)}$	$\frac{8.31 \times 10^7\ gm_m\text{-}cm^2}{sec^2 (gm_m\text{-}mole)°K}$	$\frac{8.31 \times 10^7\ dyne\text{-}cm}{(gm_m - mole)\text{-}°K}$
molecular weight	M	$\frac{mass}{(mass - mole)}$	$\frac{\frac{(force)(time)^2}{length}}{\left[\frac{(force)(time)^2}{(length)} - mole\right]length}$ $\frac{mass}{(mass - mole)}$			$\frac{gm_m}{gm_m - mole}$	$\frac{gm_m}{(gm_m\text{-}mole)}$
pressure	P	$\frac{force}{area}$	$\frac{force}{(length)^2}$ $\frac{mass}{(length)(time)^2}$			$\frac{gm}{cm\text{-}sec^2}$	$\frac{dyne}{cm^2}$
weight	W	force due to gravity	force $\frac{(mass)(length)}{(time)^2}$			$\frac{gm_m\text{-}cm}{sec^2}$	dyne
specific weight	w	$\frac{weight}{volume}$	$\frac{force}{(length)^3}$ $\frac{mass}{(length)^2(time)^2}$			$\frac{gm_m}{cm^2 - sec^2}$	$\frac{dyne}{cm^3}$
viscosity	μ	$\frac{mass}{(length)(time)}$	$\frac{(force)(time)}{(length)^2}$ $\frac{mass}{(length)(time)}$			$\frac{gm_m}{cm - sec}$	$\frac{gm_m}{cm\text{-}sec}$
kinematic viscosity	ν	$\frac{viscosity}{density}$	$\frac{(length)^2}{time}$			$\frac{cm^2}{sec}$	$\frac{cm^2}{sec}$
					Column number	1	2

	ABSOLUTE				GRAVITA		
	MASS-LENGTH-TIME				FORCE-LENGTH-TIME		
	Metric		English		Metric	English	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$\frac{ft-lb_f}{sec-°R}$	$\frac{ft-lb}{slug}$
	[illegible]	[illegible]	$\frac{ft}{sec^2}$	$\frac{ft}{sec^2}$	$\frac{cm}{sec^2}$	$\frac{ft}{sec^2}$	$\frac{ft}{sec}$
force	$\frac{gm_m-cm}{sec^2}$	dyne	$\frac{lb_m-ft}{sec^2}$	poundal	gm_f	lb_f	
	[illegible]	[illegible]	$\frac{ft}{sec^2}$	$\frac{ft}{sec^2}$	$\frac{cm}{sec^2}$	$\frac{ft}{sec^2}$	$\frac{ft}{sec}$
	(1) dimensionless	(1) $\frac{gm_m-cm}{dyne-sec^2}$	(1) dimensionless	(1) $\frac{lb_m-ft}{poundal-sec^2}$	(1) dimensionless	(1) dimensionless	(1) $\frac{slug}{lb_f}$
(force)(time)^2 / (length)	gm_m	gm_m	lb_m	lb_m	$\frac{gm_f-sec^2}{cm}$	$\frac{lb_f-sec^2}{ft}$	
(force)(time)^2 / (length)^4	$\frac{gm_m}{cm^3}$	$\frac{gm_m}{cm^3}$	$\frac{lb_m}{ft^3}$	$\frac{lb_m}{ft^3}$	$\frac{gm_f-sec^2}{cm^4}$	$\frac{lb_f-sec^2}{ft^4}$	
(force)(length) / (mass-mole)(time)	[illegible]	[illegible]	[illegible]	[illegible]	$\frac{8.31 \times 10^7 gm_f-cm}{\left(\frac{gm_f-sec^2}{cm}-mole\right)°K}$	$\frac{4.97 \times 10^4 lb_f-ft}{\left(\frac{lb_f-sec^2}{ft}-mole\right)°R}$	$\frac{4.97 \times 10^4}{(slug-mol}$
(force)(time)^2 / [-mole](length)	$\frac{gm_m}{gm_m-mole}$	$\frac{gm_m}{(gm_m-mole)}$	$\frac{lb_m}{(lb_m-mole)}$	$\frac{lb_m}{(lb_m-mole)}$	$\frac{gm_f-sec^2}{cm\left(\frac{gm_f-sec^2}{cm}-mole\right)}$	$\frac{lb_f-sec^2}{\left(\frac{lb_f-sec^2}{ft}-mole\right)ft}$	
force / (length)^2	$\frac{gm_m}{cm-sec^2}$	$\frac{dyne}{cm^2}$	$\frac{lb_m}{ft-sec^2}$	$\frac{poundal}{ft^2}$	$\frac{gm_f}{cm^2}$	$\frac{lb_f}{ft^2}$	
force	$\frac{gm_m-cm}{sec^2}$	dyne	$\frac{lb_m-ft}{sec^2}$	poundal	gm_f	lb_f	
force / (length)^3	$\frac{gm_m}{cm^2-sec^2}$	$\frac{dyne}{cm^3}$	$\frac{lb_m}{ft^2-sec^2}$	$\frac{poundal}{ft^3}$	$\frac{gm_f}{cm^3}$	$\frac{lb_f}{ft^3}$	
(force)(time) / (length)^2	$\frac{gm_m}{cm-sec}$	$\frac{gm_m}{cm-sec}$	$\frac{lb_m}{ft-sec}$	$\frac{lb_m}{ft-sec}$	$\frac{gm_f-sec}{cm^2}$	$\frac{lb_f-sec}{ft^2}$	
	$\frac{cm^2}{sec}$	$\frac{cm^2}{sec}$	$\frac{ft^2}{sec}$	$\frac{ft^2}{sec}$	$\frac{cm^2}{sec}$	$\frac{ft^2}{sec}$	$\frac{ft}{sec}$
lumn number	1	2	3	4	5	6	7

TIONAL	ENGINEERING FORCE-MASS-LENGTH-TIME		Dimensional System
	Metric	English	Systems of Units of Measurement ←
t-sec °R	$\frac{cm-gm_f gm_m}{sec - °K}$	$\frac{ft-lb_f - lb_m}{sec - °R}$	
2	$\frac{cm}{sec^2}$	$\frac{ft}{sec^2}$	
lb_f	gm_f	lb_f	
2	$\frac{cm}{sec^2}$	$\frac{ft}{sec^2}$	
g-ft -sec^2	$981 \frac{gm_m-cm}{gm_f-sec^2}$	$32.2 \frac{lb_m - ft}{lb_f - sec^2}$	
slug	gm_m	lb_m	
$\frac{slug}{ft^3}$	$\frac{gm_m}{cm^3}$	$\frac{lb_m}{ft^3}$	
lb_{f-ft} e) °R	$\frac{8.47 \times 10^4\ gm_f-cm}{(gm_m-mole)\ °K}$	$1544 \frac{lb_f-ft}{(lb_m-mole)\ °R}$	
slug slug-mole)	$\frac{gm_m}{(gm_m - mole)}$	$\frac{lb_m}{(lb_m-mole)}$	
$\frac{lb_f}{ft^2}$	$\frac{gm_f}{cm^2}$	$\frac{lb_f}{ft^2}$	
lb_f	gm_f	lb_f	
$\frac{lb_f}{ft^3}$	$\frac{gm_f}{cm^3}$	$\frac{lb_f}{ft^3}$	
$\frac{lb_f-sec}{ft^2}$	$\frac{gm_m}{cm-sec}$	$\frac{lb_m}{ft-sec}$	
2	$\frac{cm^2}{sec}$	$\frac{ft^2}{sec}$	
	8	9	

VALUES AND LOGARITHMS OF EXPONENTIAL FUNCTIONS

Note: If $0 < x < .01$ the value for e^{-x} can be found by the use of $(1-x)$ or the value for e^x can be found by the use of $(1+x)$.

x	e^x		e^{-x}	x	e^x		e^{-x}
	Value	Log$_{10}$	Value		Value	Log$_{10}$	Value
0.00	1.0000	.00000	1.00000	0.50	1.6487	.21715	.60653
0.01	1.0101	.00434	.99005	0.51	1.6653	.22149	.60050
0.02	1.0202	.00869	.98020	0.52	1.6820	.22583	.59452
0.03	1.0305	.01303	.97045	0.53	1.6989	.23018	.58860
0.04	1.0408	.01737	.96079	0.54	1.7160	.23452	.58275
0.05	1.0513	.02171	.95123	0.55	1.7333	.23886	.57695
0.06	1.0618	.02606	.94176	0.56	1.7507	.24320	.57121
0.07	1.0725	.03040	.93239	0.57	1.7683	.24755	.56553
0.08	1.0833	03474	.92312	0.58	1.7860	.25189	.55990
0.09	1.0942	03909	.91393	0.59	1.8040	.25623	.55433
0.10	1.1052	.04343	.90484	0.60	1.8221	.26058	.54881
0.11	1.1163	.04777	.89583	0.61	1.8404	.26492	.54335
0.12	1.1275	.05212	.88692	0.62	1.8589	.26926	.53794
0.13	1.1388	.05646	.87809	0.63	1.8776	.27361	.53259
0.14	1.1503	.06080	.86936	0.64	1.8965	.27795	.52729
0.15	1.1618	.06514	.86071	0.65	1.9155	.28229	.52205
0.16	1.1735	.06949	.85214	0.66	1.9348	.28664	.51685
0.17	1.1853	.07383	.84366	0.67	1.9542	.29098	.51171
0.18	1.1972	.07817	.83527	0.68	1.9739	.29532	.50662
0.19	1.2092	.08252	.82696	0.69	1.9937	.29966	.50158
0.20	1.2214	.08686	.81873	0.70	2.0138	.30401	.49659
0.21	1.2337	.09120	.81058	0.71	2.0340	.30835	.49164
0.22	1.2461	.09554	.80252	0.72	2.0544	.31269	.48675
0.23	1.2586	.09989	.79453	0.73	2.0751	.31703	.48191
0.24	1.2712	.10423	.78663	0.74	2.0959	.32138	.47711
0.25	1.2840	.10857	.77880	0.75	2.1170	.32572	.47237
0.26	1.2969	.11292	.77105	0.76	2.1383	.33006	.46767
0.27	1.3100	.11726	.76338	0.77	2.1598	.33441	.46301
0.28	1.3231	.12160	.75578	0.78	2.1815	.33875	.45841
0.29	1.3364	.12595	.74826	0.79	2.2034	.34309	.45384
0.30	1.3499	.13029	.74082	0.80	2.2255	.34744	.44933
0.31	1.3634	.13463	.73345	0.81	2.2479	.35178	.44486
0.32	1.3771	.13897	.72615	0.82	2.2705	.35612	.44043
0.33	1.3910	.14332	.71892	0.83	2.2933	.36046	.43605
0.34	1.4049	.14766	.71177	0.84	2.3164	.36481	.43171
0.35	1.4191	.15200	.70469	0.85	2.3396	.36915	.42741
0.36	1.4333	.15635	.69768	0.86	2.3632	.37349	.42316
0.37	1.4477	.16069	.69073	0.87	2.3869	.37784	.41895
0.38	1.4623	.16503	.68386	0.88	2.4109	.38218	.41478
0.39	1.4770	.16937	.67706	0.89	2.4351	.38652	.41066
0.40	1.4918	.17372	.67032	0.90	2.4596	.39087	.40657
0.41	1.5068	.17806	.66365	0.91	2.4843	.39521	.40252
0.42	1.5220	.18240	.65705	0.92	2.5093	.39955	.39852
0.43	1.5373	.18675	.65051	0.93	2.5345	.40389	.39455
0.44	1.5527	.19109	.64404	0.94	2.5600	.40824	.39063
0.45	1.5683	.19543	.63763	0.95	2.5857	.41258	.38674
0.46	1.5841	.19978	.63128	0.96	2.6117	.41692	.38289
0.47	1.6000	.20412	.62500	0.97	2.6379	.42127	.37908
0.48	1.6161	.20846	.61878	0.98	2.6645	.42561	.37531
0.49	1.6323	.21280	.61263	0.99	2.6912	.42995	.37158
0.50	1.6487	.21715	.60653	1.00	2.7183	.43429	.36788

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VALUES AND LOGARITHMS OF EXPONENTIAL FUNCTIONS

(continued)

x	e^x		e^{-x}	x	e^x		e^{-x}
	Value	Log$_{10}$	Value		Value	Log$_{10}$	Value
1.00	2.7183	.43429	.36788	1.50	4.4817	.65144	.22313
1.01	2.7456	.43864	.36422	1.51	4.5267	.65578	.22091
1.02	2.7732	.44298	.36060	1.52	4.5722	.66013	.21871
1.03	2.8011	.44732	.35701	1.53	4.6182	.66447	.21654
1.04	2.8292	.45167	.35345	1.54	4.6646	.66881	.21438
1.05	2.8577	.45601	.34994	1.55	4.7115	.67316	.21225
1.06	2.8864	.46035	.34646	1.56	4.7588	.67750	.21014
1.07	2.9154	.46470	.34301	1.57	4.8066	.68184	.20805
1.08	2.9447	.46904	.33960	1.58	4.8550	.68619	.20598
1.09	2.9743	.47338	.33622	1.59	4.9037	.69053	.20393
1.10	3.0042	.47772	.33287	1.60	4.9530	.69487	.20190
1.11	3.0344	.48207	.32956	1.61	5.0028	.69921	.19989
1.12	3.0649	.48641	.32628	1.62	5.0531	.70356	.19790
1.13	3.0957	.49075	.32303	1.63	5.1039	.70790	.19593
1.14	3.1268	.49510	.31982	1.64	5.1552	.71224	.19398
1.15	3.1582	.49944	.31664	1.65	5.2070	.71659	.19205
1.16	3.1899	.50378	.31349	1.66	5.2593	.72093	.19014
1.17	3.2220	.50812	.31037	1.67	5.3122	.72527	.18825
1.18	3.2544	.51247	.30728	1.68	5.3656	.72961	.18637
1.19	3.2871	.51681	.30422	1.69	5.4195	.73396	.18452
1.20	3.3201	.52115	.30119	1.70	5.4739	.73830	.18268
1.21	3.3535	.52550	.29820	1.71	5.5290	.74264	.15087
1.22	3.3872	.52984	.29523	1.72	5.5845	.74699	.17907
1.23	3.4212	.53418	.29229	1.73	5.6407	.75133	.17728
1.24	3.4556	.53853	.28938	1.74	5.6973	.75567	.17552
1.25	3.4903	.54287	.28650	1.75	5.7546	.76002	.17377
1.26	3.5254	.54721	.28365	1.76	5.8124	.76436	.17204
1.27	3.5609	.55155	.28083	1.77	5.8709	.76870	.17033
1.28	3.5966	.55590	.27804	1.78	5.9299	.77304	.16864
1.29	3.6328	.56024	.27527	1.79	5.9895	.77739	.16696
1.30	3.6693	.56458	.27253	1.80	6.0496	.78173	.16530
1.31	3.7062	.56893	.26982	1.81	6.1104	.78607	.16365
1.32	3.7434	.57327	.26714	1.82	6.1719	.79042	.16203
1.33	3.7810	.57761	.26448	1.83	6.2339	.79476	.16041
1.34	3.8190	.58195	.26185	1.84	6.2965	.79910	.15882
1.35	3.8574	.58630	.25924	1.85	6.3598	.80344	15724
1.36	3.8962	.59064	.25666	1.86	6.4237	.80779	.15567
1.37	3.9354	.69498	.25411	1.87	6.4883	.81213	.15412
1.38	3.9749	.59933	.25158	1.88	6.5535	.81647	.15259
1.39	4.0149	.60367	.24908	1.89	6.6194	.82082	.15107
1.40	4.0552	.60801	.24660	1.90	6.6859	.82516	.14957
1.41	4.0960	.61236	.24414	1.91	6.7531	.82950	.14808
1.42	4.1371	.61670	.24171	1.92	6.8210	.83385	14661
1.43	4.1787	.62104	.23931	1.93	6.8895	.83819	.14515
1.44	4.2207	.62538	.23693	1.94	6.9588	.84253	.14370
1.45	4.2631	.62973	.23457	1.95	7.0287	.84687	.14227
1.46	4.3060	.63407	.23224	1.96	7.0993	.85122	.14086
1.47	4.3492	.63841	.22993	1.97	7.1707	.85556	.13946
1.48	4.3929	.64276	.22764	1.98	7.2427	.85990	.13807
1.49	4.4371	.64710	.22537	1.99	7.3155	.86425	.13670
1.50	4.4817	.65144	.22313	2.00	7.3891	.86859	.13534

VALUES AND LOGARITHMS OF EXPONENTIAL FUNCTIONS

(continued)

x	e^x		e^{-x}	x	e^x		e^{-x}
	Value	Log$_{10}$	Value		Value	Log$_{10}$	Value
2.00	7.3891	.86859	.13534	2.50	12.182	1.08574	.08208
2.01	7.4633	.87293	.13399	2.51	12.305	1.09008	.08127
2.02	7.5383	.87727	.13266	2.52	12.429	1.09442	.08046
2.03	7.6141	.88162	.13134	2.53	12.554	1.09877	.07966
2.04	7.6906	.88596	.13003	2.54	12.680	1.10311	.07887
2.05	7.7679	.89030	.12873	2.55	12.807	1.10745	.07808
2.06	7.8460	.89465	.12745	2.56	12.936	1.11179	.07730
2.07	7.9248	.89899	.12619	2.57	13.066	1.11614	.07654
2.08	8.0045	.90333	.12493	2.58	13.197	1.12048	.07577
2.09	8.0849	.90768	.12369	2.59	13.330	1.12482	.07502
2.10	8.1662	.91202	.12246	2.60	13.464	1.12917	.07427
2.11	8.2482	.91636	.12124	2.61	13.599	1.13351	.07353
2.12	8.3311	.92070	.12003	2.62	13.736	1.13785	.07280
2.13	8.4149	.92505	.11884	2.63	13.874	1.14219	.07208
2.14	8.4994	.92939	.11765	2.64	14.013	1.14654	.07136
2.15	8.5849	.93373	.11648	2.65	14.154	1.15088	.07065
2.16	8.6711	.93808	.11533	2.66	14.296	1.15522	.06995
2.17	8.7583	.94242	.11418	2.67	14.440	1.15957	.06925
2.18	8.8463	.94676	.11304	2.68	14.585	1.16391	.06856
2.19	8.9352	.95110	.11192	2.69	14.732	1.16825	.06788
2.20	9.0250	.95545	.11080	2.70	14.880	1.17260	.06721
2.21	9.1157	.95979	.10970	2.71	15.029	1.17694	.06654
2.22	9.2073	.96413	.10861	2.72	15.180	1.18128	.06587
2.23	9.2999	.96848	.10753	2.73	15.333	1.18562	.06522
2.24	9.3933	.97282	.10646	2.74	15.487	1.18997	.06457
2.25	9.4877	.97716	.10540	2.75	15.643	1.19431	.06393
2.26	9.5831	.98151	.10435	2.76	15.800	1.19865	.06329
2.27	9.6794	.98585	.10331	2.77	15.959	1.20300	.06266
2.28	9.7767	.99019	.10228	2.78	16.119	1.20734	.06204
2.29	9.8749	.99453	.10127	2.79	16.281	1.21168	.06142
2.30	9.9742	.99888	.10026	2.80	16.445	1.21602	.06081
2.31	10.074	1.00322	.09926	2.81	16.610	1.22037	.06020
2.32	10.176	1.00756	.09827	2.82	16.777	1.22471	.05961
2.33	10.278	1.01191	.09730	2.83	16.945	1.22905	.05901
2.34	10.381	1.01625	.09633	2.84	17.116	1.23340	.05843
2.35	10.486	1.02059	.09537	2.85	17.288	1.23774	.05784
2.36	10.591	1.02493	.09442	2.86	17.462	1.24208	.05727
2.37	10.697	1.02928	.09348	2.87	17.637	1.24643	.05670
2.38	10.805	1.03362	.09255	2.88	17.814	1.25077	.05613
2.39	10.913	1.03796	.09163	2.89	17.993	1.25511	.05558
2.40	11.023	1.04231	.09072	2.90	18.174	1.25945	.05502
2.41	11.134	1.04665	.08982	2.91	18.357	1.26380	.05448
2.42	11.246	1.05099	.08892	2.92	18.541	1.26814	.05393
2.43	11.359	1.05534	.08804	2.93	18.728	1.27248	.05340
2.44	11.473	1.05968	.08716	2.94	18.916	1.27683	.05287
2.45	11.588	1.06402	.08629	2.95	19.106	1.28117	.05234
2.46	11.705	1.06836	.08543	2.96	19.298	1.28551	.05182
2.47	11.822	1.07271	.08458	2.97	19.492	1.28985	.05130
2.48	11.941	1.07705	.08374	2.98	19.688	1.29420	.05079
2.49	12.061	1.08139	.08291	2.99	19.886	1.29854	.05029
2.50	12.182	1.08574	.08208	3.00	20.086	1.30288	.04979

VALUES AND LOGARITHMS OF EXPONENTIAL FUNCTIONS
(continued)

x	e^x		e^{-x}
	Value	Log_{10}	Value
3.00	20.086	1.30288	.04979
3.05	21.115	1.32460	.04736
3.10	22.198	1.34631	.04505
3.15	23.336	1.36803	.04285
3.20	24.533	1.38974	.04076
3.25	25.790	1.41146	.03877
3.30	27.113	1.43317	.03688
3.35	28.503	1.45489	.03508
3.40	29.964	1.47660	.03337
3.45	31.500	1.49832	.03175
3.50	33.115	1.52003	.03020
3.55	34.813	1.54175	.02872
3.60	36.598	1.56346	.02732
3.65	38.475	1.58517	.02599
3.70	40.447	1.60689	.02472
3.75	42.521	1.62860	.02352
3.80	44.701	1.65032	.02237
3.85	46.993	1.67203	.02128
3.90	49.402	1.69375	.02024
3.95	51.935	1.71546	.01925
4.00	54.598	1.73718	.01832
4.10	60.340	1.78061	.01657
4.20	66.686	1.82404	.01500
4.30	73.700	1.86747	.01357
4.40	81.451	1.91090	.01227
4.50	90.017	1.95433	.01111
4.60	99.484	1.99775	.01005
4.70	109.95	2.04118	.00910
4.80	121.51	2.08461	.00823
4.90	134.29	2.12804	.00745
5.00	148.41	2.17147	.00674
5.10	164.02	2.21490	.00610
5.20	181.27	2.25833	.00552
5.30	200.34	2.30176	.00499
5.40	221.41	2.34519	.00452
5.50	244.69	2.38862	.00409
5.60	270.43	2.43205	.00370
5.70	298.87	2.47548	.00335
5.80	330.30	2.51891	.00303
5.90	365.04	2.56234	.00274
6.00	403.43	2.60577	.00248
6.25	518.01	2.71434	.00193
6.50	665.14	2.82291	.00150
6.75	854.06	2.93149	.00117
7.00	1096.6	3.04006	.00091
7.50	1808.0	3.25721	.00055
8.00	2981.0	3.47436	.00034
8.50	4914.8	3.69150	.00020
9.00	8103.1	3.90865	.00012
9.50	13360.	4.12580	.00007
10.00	22026.	4.34294	.00005

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CONVERSION FACTORS - TEMPERATURE

Desired Units Given Units	°F	°C	°R	°K
Degrees Fahr.		.5555 x (°F - 32)	°F + 460	.5555 x (°F-32) + 273
Degrees Centigrade	1.8°C + 32		1.8°C + 492	°C + 273
Degrees Rankin	°R - 460	.5555 x (°R - 492)		.5555 x (°R-492) + 273
Degrees Kelvin	1.8(°K-273) + 32	°K - 273	1.8(°K-273)+492	

CONVERSION FACTORS - PRESSURE

Desired units / Given units	$\frac{gm_m}{cm\text{-}sec^2}$	$\frac{dynes}{cm^2}$	$\frac{\#_m}{ft\text{-}sec^2}$	$\frac{poundals}{ft^2}$	$\frac{gm_f}{cm^2}$	$\frac{\#_f}{ft^2}$	$\frac{\#_f}{in^2}$	Atmospheres
$\frac{gm_m}{cm\text{-}sec^2}$	1	1	6.7197×10^{-2}	6.7197×10^{-2}	1.0197×10^{-3}	2.0885×10^{-3}	1.4504×10^{-5}	9.8692×10^{-7}
$\frac{dynes}{cm^2}$	1	1	6.7197×10^{-2}	6.7197×10^{-2}	1.0197×10^{-3}	2.0885×10^{-3}	1.4504×10^{-5}	9.8692×10^{-7}
$\frac{\#_m}{ft\text{-}sec^2}$	14.882	14.882	1	1	1.5175×10^{-2}	3.1081×10^{-2}	2.1584×10^{-4}	1.4687×10^{-5}
$\frac{poundals}{ft^2}$	14.882	14.882	1	1	1.5175×10^{-2}	3.1081×10^{-2}	2.1584×10^{-4}	1.4687×10^{-5}
$\frac{gm_f}{cm^2}$	980.665	980.665	65.898	65.898	1	2.0482	1.4223×10^{-2}	9.6784×10^{-4}
$\frac{\#_f}{ft^2}$	478.80	478.80	32.174	32.174	4.8824×10^{-1}	1	6.9444×10^{-3}	4.7254×10^{-4}
$\frac{\#_f}{in^2}$	6.8948×10^4	6.8948×10^4	4.6331×10^3	4.6331×10^3	70.307	144.00	1	6.8046×10^{-2}
Atmospheres	1.0133×10^6	1.0133×10^6	6.8087×10^4	6.8087×10^4	1.0332×10^3	2.1162×10^3	14.696	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

CONVERSION FACTORS - AREA

Desired Units / Given Units	Square Inch	Square Feet	Square Yard	Square Mile	Acre	Square Centimeter	Square Decimeter	Square Meter	Square Kilometer
Square Inch	1	6.9444×10^{-3}	77.1605×10^{-5}	2.49×10^{-10}	15.94×10^{-6}	6.452	6.452×10^{-2}	6.452×10^{-4}	6.452×10^{-10}
Square Foot	144	1	0.1111	3.587×10^{-8}	2.296×10^{-5}	929.0341	929.0341×10^{-2}	929.0341×10^{-4}	929.0341×10^{-10}
Square Yard	1296	9	1	3.228×10^{-7}	2.066×10^{-4}	83.61×10^{2}	83.61	83.61×10^{-2}	83.61×10^{-8}
Square Mile	40.144×10^{8}	2.788×10^{7}	3.098×10^{6}	1	640	2.589998×10^{10}	2.589998×10^{8}	2.589998×10^{6}	2.589998
Acre	62.73×10^{7}	4.3560×10^{4}	4840	15.625×10^{-4}	1	4046.873×10^{4}	4046.873×10^{2}	4046.873	4046.873×10^{-6}
Square Centimeter	15.5×10^{-2}	10.764×10^{-4}	1.1960×10^{-4}	3.8610×10^{-11}	2.471×10^{-8}	1	1×10^{-2}	1×10^{-4}	1×10^{-10}
Square Decimeter	15.5	10.764×10^{-2}	1.1960×10^{-2}	3.8610×10^{-9}	2.471×10^{-6}	1×10^{2}	1	1×10^{-2}	1×10^{-8}
Square Meter	15.5×10^{2}	10.764	1.1960	3.8610×10^{-7}	2.471×10^{-4}	1×10^{4}	1×10^{2}	1	1×10^{-6}
Square Kilometer	15.5×10^{8}	10.764×10^{6}	1.1960×10^{6}	3.8610×10^{-1}	2.471×10^{2}	1×10^{10}	1×10^{8}	1×10^{6}	1

To convert a value from a given unit a desired unit, multiply the given value by the factor opposite the given units and beneath the desired unit

CONVERSION FACTORS – VOLUME

Desired Units / Given Units	Cubic Yard	Cubic Foot	Cubic Inch	Cubic Meter	Cubic Decimeter	Cubic Centimeter	Liter
Cubic Yard	1	27	4.6656×10^{4}	0.764559	764.559	7.64559×10^{5}	764.54
Cubic Foot	3.7037×10^{-2}	1	1728	2.8317×10^{-2}	28.317	2.8317×10^{4}	28.316
Cubic Inch	2.143347×10^{-5}	5.78704×10^{-4}	1	1.63872×10^{-5}	1.63872×10^{-2}	16.3872	1.63868×10^{-2}
Cubic Meter	1.30794	35.314445	6.1023×10^{4}	1	1000	1×10^{6}	999.973
Cubic Decimeter	1.3079×10^{-3}	3.5314×10^{-2}	61.023	0.001	1	1000	.99997
Cubic Centimeter	1.3079×10^{-6}	3.5314×10^{-5}	6.1023×10^{-2}	1×10^{-6}	1×10^{-3}	1	9.99973×10^{-4}
Liter	1.3080×10^{-3}	3.5316×10^{-2}	61.025	1.000027×10^{-3}	1.000027	1000.027	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

CONVERSION FACTORS - FLOW

Desired Units / Given Units	$\frac{M^3}{sec}$	$\frac{M^3}{min}$	$\frac{M^3}{hour}$	$\frac{ft^3}{sec}$	$\frac{ft^3}{min}$	$\frac{ft^3}{hour}$	$\frac{L}{sec}$	$\frac{L}{min}$	$\frac{cm^3}{sec}$	$\frac{cm^3}{min}$
$\frac{M^3}{sec}$	1	60	3600	35.3144	21.1887×10^{2}	12.7132×10^{4}	999.973	59.998×10^{3}	1×10^{6}	6×10^{7}
$\frac{M^3}{min}$	0.0167	1	60	0.5886	35.3144	21.189×10^{2}	16.667	999.973	16.667×10^{3}	1×10^{6}
$\frac{M^3}{hour}$	2.778×10^{-5}	16.667×10^{-3}	1	98.90×10^{-4}	0.5886	35.3144	27.777×10^{-2}	16.667	2.777×10^{2}	1.666×10^{4}
$\frac{ft^3}{sec}$	28.317×10^{-3}	1.699	101.94	1	60	3600	28.316	16.9896×10^{2}	2.8317×10^{4}	1.699×10^{6}
$\frac{ft^3}{min}$	4.7195×10^{-4}	28.317×10^{-3}	1.699	16.667×10^{-3}	1	60	47.193×10^{-2}	28.316	4.7195×10^{2}	2.8317
$\frac{ft^3}{hour}$	7.8658×10^{-6}	4.7195×10^{-4}	28.317×10^{-3}	2.778×10^{-4}	16.667×10^{-3}	1	7.866×10^{-3}	0.4719	78.658	4.7195×10^{2}
$\frac{L}{sec}$	1.000027×10^{-3}	6.00016×10^{-2}	3.6	35.316×10^{-3}	2.11896	127.138	1	60	1000.027	16.667
$\frac{L}{min}$	1.6667×10^{-5}	1.000027×10^{-3}	6.0016×10^{-2}	5.886×10^{-4}	35.316×10^{-3}	2.11896	1.6667×10^{-2}	1	16.667	1000.027
$\frac{cm^3}{sec}$	1×10^{-6}	6×10^{-5}	3.6×10^{-3}	3.5314×10^{-5}	2.1189×10^{-3}	1.271×10^{-3}	9.99973×10^{-4}	5.9998×10^{-2}	1	16.667×10^{-3}
$\frac{cm^3}{min}$	1.6667×10^{-8}	1×10^{-6}	6×10^{-5}	5.886×10^{-7}	0.3531×10^{-4}	2.11887×10^{-3}	5.9998×10^{-2}	9.99973×10^{-4}	60	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired unit.

CONVERSION FACTORS WEIGHT

Desired Units / Given Units	Micro-gram	Milli-gram	gram	Kilo-gram	grain	Ounce (avdp)	Pound (avdp)	Ton (U.S. short)	Tonne (metric)
Micro-gram	1	1×10^{-3}	1×10^{-6}	1×10^{-9}	15.4124×10^{-6}	3.5274×10^{-8}	2.2046×10^{-9}	1.1023×10^{-12}	1×10^{-12}
Milli-gram	1×10^{3}	1	1×10^{-3}	1×10^{-6}	15.4324×10^{-3}	3.5274×10^{-5}	2.2046×10^{-6}	1.1023×10^{-9}	1×10^{-9}
gram	1×10^{6}	1×10^{3}	1	1×10^{-3}	15.4324	3.5274×10^{-2}	2.2046×10^{-3}	1.1023×10^{-6}	1×10^{-6}
Kilogram	1×10^{9}	1×10^{6}	1×10^{3}	1	15.4324×10^{3}	35.274	2.2046	1.1023×10^{-3}	1×10^{-3}
grain	64.799×10^{3}	64.799	64.799×10^{-3}	64.799×10^{-6}	1	22.857×10^{-4}	1.4286×10^{-4}	7.143×10^{-8}	64.799×10^{-9}
Ounce (avdp)	28.349×10^{6}	28.349×10^{3}	28.349	28.349×10^{-3}	437.5	1	62.5×10^{-3}	3.125×10^{-5}	28.349×10^{-6}
Pound (avdp)	453.59×10^{6}	453.59×10^{3}	453.59	453.59×10^{-3}	7000	16	1	5×10^{-4}	453.59×10^{-6}
Ton (US short)	905.185×10^{9}	907.185×10^{6}	907.185×10^{3}	907.185	14×10^{6}	3.2×10^{4}	2000	1	0.907185
Tonne (metric)	1×10^{12}	1×10^{9}	1×10^{6}	1×10^{3}	1.543×10^{7}	3.5274×10^{4}	2204.62	1.10231	1

CONVERSION FACTORS - CONCENTRATION

Desired Units / Given Units	$\mu g/M^3$	$\mu g/M^3$	$\mu g/L$	oz/ft.^{3}	lbs./ft.^{3}	grams/ft.^{3}	lbs./1000 ft.^{3}	grains/ft.^{3}
$\mu g/M^3$	1	1000	1.000027	9.989×10^{-7}	6.243×10^{-8}	2.8317×10^{-5}	6.243×10^{-5}	4.37×10^{-4}
$\mu g/M^3$	1×10^{-3}	1	1.000027×10^{-3}	9.989×10^{-10}	6.243×10^{-11}	2.8317×10^{-8}	6.243×10^{-8}	4.37×10^{-7}
$\mu g/L$	.999973	9.99973×10^2	1	9.988×10^{-7}	6.242×10^{-8}	2.8316×10^{-5}	6.242×10^{-5}	4.37×10^{-4}
oz/ft.^{3}	1.00115×10^6	1.00115×10^9	1.00118×10^6	1	62.5×10^{-3}	28.349	62.5	4.375×10^2
lbs./ft.^{3}	1.602×10^7	1.602×10^{10}	1.602×10^7	16	1	453.59	1×10^3	7×10^3
grams/ft.^{3}	3.531×10^4	3.531×10^7	3.531×10^4	3.5274×10^{-2}	2.20462×10^{-3}	1	2.2046	15.43
lbs./1000 ft.^{3}	1.602×10^4	1.602×10^7	1.602×10^4	1.6×10^{-2}	1×10^{-3}	453.59×10^{-3}	1	7
grains/ft.^{3}	2.288×10^3	2.288×10^6	2.288×10^3	2.2857×10^3	1.4286×10^{-4}	6.4799×10^{-2}	14.286	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired unit.

CONVERSION FACTORS - LENGTH

Given Units \ Desired Units	Inch	Foot	Yard	Mile	Micron	Millimeter	Centimeter	Meter	Kilometer
Inch	1	83.33 $\times 10^{-3}$	27.778 $\times 10^{-3}$	1.578 $\times 10^{-5}$	2.54 $\times 10^{4}$	25.4	2.54	2.54 $\times 10^{-2}$	2.54 $\times 10^{-5}$
Foot	12	1	3333	1.894 $\times 10^{-4}$	30.48 $\times 10^{4}$	304.8	30.48	30.48 $\times 10^{-2}$	30.48 $\times 10^{-5}$
Yard	36	3	1	5.682 $\times 10^{-4}$	91.44 $\times 10^{4}$	914.4	91.44	91.44 $\times 10^{-2}$	91.44 $\times 10^{-5}$
Mile	6.3360 $\times 10^{4}$	5280	1760	1	1.6094 $\times 10^{9}$	1.6094 $\times 10^{6}$	1.6094 $\times 10^{5}$	1.6094 $\times 10^{3}$	1.6094
Micron	3.937 $\times 10^{-5}$	32.808 $\times 10^{-7}$	10.94 $\times 10^{-7}$	62.137 $\times 10^{-11}$	1	1×10^{-3}	1×10^{-4}	1×10^{-6}	1×10^{-9}
Millimeter	3.937 $\times 10^{-2}$	32.808 $\times 10^{-4}$	10.94 $\times 10^{-4}$	62.137 $\times 10^{-8}$	1×10^{3}	1	0.1	1×10^{-3}	1×10^{-6}
Centimeter	3.937 $\times 10^{-1}$	32.808 $\times 10^{-3}$	10.94 $\times 10^{-3}$	62.137 $\times 10^{-7}$	1×10^{4}	10	1	1×10^{-2}	1×10^{-5}
Meter	39.37	32.808 $\times 10^{-1}$	10.94 $\times 10^{-1}$	62.137 $\times 10^{-5}$	1×10^{6}	1×10^{3}	1×10^{2}	1	1×10^{-3}
Kilometer	3.937 $\times 10^{4}$	32.808 $\times 10^{2}$	10.94 $\times 10^{2}$	62.137 $\times 10^{-2}$	1×10^{9}	1×10^{6}	1×10^{5}	1×10^{3}	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

CONVERSION FACTORS - EMISSION RATES

Desired units / Given units	gms/sec	gms/min	kg/hr	kg/day	lbs/min	lbs/hr	lbs/day	tons/hr	tons/day	tons/yr
gms/sec	1.0	60.0	3.6	8.640 X 10	1.3228 X 10^{-1}	7.9367	1.9048 X 10^{2}	3.9683 X 10^{-3}	9.5240 X 10^{-2}	3.4763 X 10
gms/min	1.6667 X 10^{-2}	1.0	6.0 X 10^{-2}	1.4400	2.2046 X 10^{-3}	1.3228 X 10^{-1}	3.1747	6.6139 X 10^{-5}	1.5873 X 10^{-3}	5.7938 X 10^{-1}
kg/hr	2.7778 X 10^{-1}	16.667	1.0	2.4000 X 10	3.6744 X 10^{-2}	2.2046	5.2911 X 10	1.1023 X 10^{-3}	2.6456 X 10^{-2}	9.6563
kg/day	1.1574 X 10^{-2}	6.9444 X 10^{-1}	4.1667 X 10^{-2}	1.0	1.5310 X 10^{-3}	9.1860 X 10^{-2}	2.2046	4.5930 X 10^{-5}	1.1023 X 10^{-3}	4.0235 X 10^{-1}
lbs/min	7.5598	4.5359 X 10^{2}	2.7215 X 10	6.5317 X 10^{2}	1.0	60.0	1.44 X 10^{3}	3.000 X 10^{-2}	7.2000 X 10^{-1}	2.6280 X 10^{2}
lbs/hr	1.2600 X 10^{-1}	7.5598	4.5359 X 10^{-1}	1.0886 X 10	1.6667 X 10^{-2}	1.0	24.0	5.0000 X 10^{-4}	1.2000 X 10^{-2}	4.3800
lbs/day	5.2499 X 10^{-3}	3.1499 X 10^{-1}	1.8900 X 10^{-2}	4.5359 X 10^{-1}	6.9444 X 10^{-4}	4.1667 X 10^{-2}	1.0	2.0833 X 10^{-5}	5.0000 X 10^{-4}	1.8250 X 10^{-1}
tons/hr	2.5199 X 10^{2}	1.5120 X 10^{4}	9.0718 X 10^{2}	2.1772 X 10^{4}	3.3333 X 10	2.0 X 10^{3}	4.8000 X 10^{4}	1.0	24.0	8.7600 X 10^{3}
tons/day	1.0500 X 10	6.2999 X 10^{2}	3.7799 X 10	9.0718 X 10^{2}	1.3889	8.3333 X 10	2.0 X 10^{3}	4.1667 X 10^{-2}	1.0	365.0
tons/yr	2.8766 X 10^{-2}	1.7260	1.0356 X 10^{-1}	2.4854	3.8052 X 10^{-3}	2.2831 X 10^{-1}	5.4795	1.1416 X 10^{-4}	2.7397 X 10^{-3}	1.0

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

CONVERSION FACTORS - VELOCITY

Desired units Given units	m/sec	ft/sec	ft/min	km/hr	mi/hr	knots	mi/day
m/sec	1.0	3.2808	1.9685 X 10^{2}	3.6	2.2369	1.9425	5.3687 X 10
ft/sec	3.0480 X 10^{-1}	1.0	60	1.0973	6.8182 X 10^{-1}	5.9209 X 10^{-1}	1.6364 X 10
ft/min	5.0080 X 10^{-3}	1.6667 X 10^{-2}	1.0	1.8288 X 10^{-2}	1.1364 X 10^{-2}	9.8681 X 10^{-3}	2.7273 X 10^{-1}
km/hr	2.7778 X 10^{-1}	9.1134 X 10^{-1}	5.4681 X 10	1.0	6.2137 X 10^{-1}	5.3959 X 10^{-1}	1.4913 X 10
mi/hr	4.4707 X 10^{-1}	1.4667	88.0	1.6093	1.0	8.6839 X 10^{-1}	24
knots	5.1479 X 10^{-1}	1.6890	1.0134 X 10^{2}	1.8533	1.1516	1.0	2.7637 X 10
mi/day	1.8627 X 10^{-2}	6.1111 X 10^{-2}	3.6667	6.7056 X 10^{-2}	4.1667 X 10^{-2}	3.6183 X 10^{-2}	1.0

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

LOGARITHMS TO BASE 10

N	0	1	2	3	4	5	6	7	8	9	Proportional Parts								
											1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	5	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

The proportional parts are stated in full for every tenth at the right-hand side. The logarithm of any number of four significant figures can be read directly by adding the proportional part corresponding to the fourth figure to the tabular number corresponding to the first three figures. There may be an error of 1 in the last place.

LOGARITHMS TO BASE 10

(continued)

N	0	1	2	3	4	5	6	7	8	9	Proportional Parts								
											1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

The proportional parts are stated in full for every tenth at the right-hand side. The logarithm of any number of four significant figures can be read directly by adding the proportional part corresponding to the fourth figure to the tabular number corresponding to the first three figures. There may be an error of 1 in the last place.

U. S. GOVERNMENT PRINTING OFFICE : 1969 [illegible]

INTERNATIONAL ATOMIC WEIGHTS

BASED ON CARBON - 12

	Symbol	Atomic Number	Atomic Weight		Symbol	Atomic Number	Atomic Weight
Actinium	Ac	89	[227] *	Mercury	Hg	80	200.59
Aluminum	Al	13	26.9815	Molybdenum	Mo	42	95.94
Americium	Am	95	[243] *	Neodymium	Nd	60	144.24
Antimony	Sb	51	121.75	Neon	Ne	10	20.183
Argon	Ar	18	39.948	Neptunium	Np	93	[237] *
Arsenic	As	33	74.9216	Nickel	Ni	28	58.71
Astatine	At	85	[210] *	Niobium	Nb	41	92.906
Barium	Ba	56	137.34	Nitrogen	N	7	14.0067
Berkelium	Bk	97	[249] *	Nobelium	No	102	[254] *
Beryllium	Be	4	9.0122	Osmium	Os	76	190.2
Bismuth	Bi	83	208.980	Oxygen	O	8	15.9994 [a]
Boron	B	5	10.811 [a]	Palladium	Pd	46	106.4
Bromine	Br	35	79.909 [b]	Phosphorus	P	15	30.9738
Cadmium	Cd	48	112.40	Platinum	Pt	78	195.09
Calcium	Ca	20	40.08	Plutonium	Pu	94	[242] *
Californium	Cf	98	[251] *	Polonium	Po	84	[210] *
Carbon	C	6	12.01115 [a]	Potassium	K	19	39.102
Cerium	Ce	58	140.12	Praseodymium	Pr	59	140.907
Cesium	Cs	55	132.905	Promethium	Pm	61	[147] *
Chlorine	Cl	17	35.453 [b]	Protactinium	Pa	91	[231] *
Chromium	Cr	24	51.996 [b]	Radium	Ra	88	[226] *
Cobalt	Co	27	58.9332	Radon	Rn	86	[222] *
Copper	Cu	29	63.54	Rhenium	Re	75	186.2
Curium	Cm	96	[247] *	Rhodium	Rh	45	102.905
Dysprosium	Dy	66	162.50	Rubidium	Rb	37	85.47
Einsteinium	Es	99	[254] *	Ruthenium	Ru	44	101.07
Erbium	Er	68	167.26	Samarium	Sm	02	150.35
Europium	Eu	63	151.96	Scandium	Sc	21	44.956
Fermium	Fm	100	[253] *	Selenium	Se	34	78.96
Fluorine	F	9	18.9984	Silicon	Si	14	28.086 [a]
Francium	Fr	87	[223] *	Silver	Ag	47	107.870 [b]
Gadolinium	Gd	64	157.25	Sodium	Na	11	22.9898
Gallium	Ga	31	69.72	Strontium	Sr	38	87.62
Germanium	Ge	32	72.59	Sulfur	S	16	32.064 [a]
Gold	Au	79	196.967	Tantalum	Ta	73	180.948
Hafnium	Hf	72	178.49	Technetium	Tc	43	[99] *
Helium	He	2	4.0026	Tellurium	Te	52	127.60
Holmium	Ho	67	164.930	Terbium	Tb	65	158.924
Hydrogen	H	1	1.00797 [a]	Thallium	Tl	81	204.37
Indium	In	49	114.82	Thorium	Th	90	232.038
Iodine	I	53	126.9044	Thulium	Tm	69	168.934
Iridium	Ir	77	192.2	Tin	Sn	50	118.69
Iron	Fe	26	55.847 [b]	Titanium	Ti	22	47.90
Krypton	Kr	36	83.80	Tungsten	W	74	183.85
Lanthanum	La	57	138.91	Uranium	U	92	238.03
Lead	Pb	82	207.19	Vanadium	V	23	50.942
Lithium	Li	3	6.939	Xenon	Xe	54	131.30
Lutetium	Lu	71	174.97	Ytterbium	Yb	70	173.04
Magnesium	Mg	12	24.312	Yttrium	Y	39	88.905
Manganese	Mn	25	54.9380	Zinc	Zn	30	65.37
Mendelevium	Md	101	[256] *	Zirconium	Zr	40	91.22

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* Value in brackets denotes the mass number of the isotope of longest known half life (or a better known one for Bk, Cf, Po, Pm and Tc).

[a] Atomic weight varies because of natural variation in isotopic composition: B, ±0.003; C, ±0.00005 H, ±0.00001; O, ±0.0001; Si, ±0.001; S, ±0.003.

[b] Atomic weight is believed to have following experimental uncertainty: Br, ±0.002; Cl, ±0.001; Cr, ±0.001, Fe, ±0.003; Ag, ±0.003. For other elements, the last digit given for the atomic weight is believed reliable to ±0.5. Lawrencium, Lw, has been proposed as the name for element No. 103, nuclidic mass about 257

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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE
Silver Spring, Md. 20910

NATIONAL WEATHER SERVICE OFFICES AND STATIONS

Eleventh Edition — January 1, 1971

1.0 General: The purposes of this publication are: To list all first- and second-order stations or offices operated by, or under the supervision of, the National Weather Service; to show the type and location of each station; and, to briefly indicate the nature of the observational program provided by each station.

2.0 Explanation of Entries: This list is an extraction of data from the "Station Information Deck" maintained by the Office of the Chief, Resources Management Staff, from information supplied by stations on Forms A3 and A1, formerly 500-3 and 500-10, etc. Wx3 should be advised of any error by memo through the regional headquarters or by new station forms when file copies indicate an error.

2.1 Station Identification and Location Data:

AIRPORT NAME - The STATION NAME is not repeated if it is a part of the airport name.

CODE		TYPE OF STATION
10	WSO	- Weather Service Office
20	NC	- National Center
30	FAA	- Federal Aviation Administration
40	WSFO	- Weather Service Forecast Office
50	RWC	- Regional Weather Center
60	RFC	- River Forecast Center
70	WSMO	- Weather Service Meteorological Observatory
80	SC	- Weather Service Office for State Climatology
90	CUA	- Cooperative Upper-air Unit
01	AMOS	- Automatic Meteorological Observing Station
02	SAWR	- Supplementary Aviation Weather Reporting
03	A	- Aviation Weather Reporting Station
04	FSS	- Flight Service Station (FAA)
05	TWR	- Control Tower (FAA)
06	CST	- Combined Flight Service Station and Tower (FAA)
07	S	- Synoptic Observations
08	SA	- Combined Synoptic and Aviation Reporting
09	CG	- Coast Guard

Examples of some possible combined types are:

12	SAWR at a WSO	15	WSO-TWR
12	FSS at a WSO	31	AMOS at a FAA

CALL	Letters assigned as location identifiers used in transmitting aviation weather reports.
NO.	Refers to the International Index Number.
LAT.	Latitude to the nearest whole minute; North, unless South is indicated.
LONG.	Longitude to the nearest whole minute; West, unless East is indicated.
ELEV.	The assigned station elevation (Hp) entered to the nearest whole foot. An entry to which "A" is appended is the elevation of the highest usable portion of the landing area of an airport; one to which "G" is appended is the elevation of the ground beneath the instrument shelter or the observing station.

2.2 Observational Data:

Synoptic Observations

S - Synoptic (6- and 3-hourly)
0 - 8 = Number of observations per day

C - Completeness and frequency of reports

1. Complete all elements coded and reported, daily
2. Abbreviated, some elements not reported, daily
3. Complete, seasonal
4. Abbreviated, seasonal
5. Complete, encoded from aviation weather report and supplemental information
6. Abbreviated, encoded from aviation weather report

Aviation Observations

AV - Number of record observations per day
01 - 24 = Number per day
25 = On call only

F - Frequency during period of day

1. Consecutive hourly
2. Not consecutive hours
3. Bi-hourly
4. Three-hourly
5. Six-hourly
6. Hourly, consecutive (not 24 hours) plus 3- or 6-hourly
9. Irregular schedule

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D - Day to day

1. Daily
2. Not 7 days a week

A - Additive data appended to aviation weather observations at 3- and 6-hourly times

0 - 8 = Number per day
9 = Non-standard format or times
A = Aviation weather reports, not transmitted on aviation weather circuits

Upper-Air

P - Pibal

W - Rawin

U - Radiosonde

L - Low-level soundings

1 - 4 = Number per day
9 = Irregular schedule, usually not at WMO times.

Radar

RR - Radar Observations from:

Code	Equipment
56, 57	WSR-57
65	WSR-57M
X1	WSR-1 or 1A
X3	WSR-3
XD	Decca
XM	WSR-4
XP	SP1M

T - Participation

1. Participates in National Weather Radar Reporting Network hourly observations
2. Same as No. 1 except limited operational status during the winter
3. Local use radar
4. Same as No. 3 except limited operational status during the winter

STATION INVENTORY

FIRST AND SECOND-ORDER STATIONS

CODE	AREA
Region	
0	South American Cooperative
1	Eastern
2	Southern (Virgin Is., San Juan)
3	Central
4	Western
5	Alaskan
6	Pacific
7	Mexican, Caribbean and West Indies
8	Arctic, Antarctic and Canada
9	Ships

HOURLY OBSERVATIONS TABLE

	REG 0	REG 1	REG 2	REG 3	REG 4	REG 5	REG 6	REG 7	REG 8	REG 9	SERVICE TOTAL
24 HRLY	0	52	57	59	47	11	11	0	0	0	[illegible]
[illegible] HRLY	0	5	4	7	6	2	2	0	1	0	[illegible]

STATION TYPE	REG 0	REG 1	REG 2	REG 3	REG 4	REG 5	REG 6	REG 7	REG 8	REG 9	SERVICE TOTAL
WSO	[illegible]	54	65	66	55	11	11	1	[illegible]	[illegible]	[illegible]
WSFI	[illegible]	[illegible]	4	[illegible]	7	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SAWR	[illegible]	[illegible]	41	[illegible]	[illegible]	17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AVIAT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FSS	[illegible]	41	[illegible]	[illegible]	[illegible]	14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TWR	[illegible]	[illegible]	21	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CST	[illegible]	[illegible]	4	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SYNOP	[illegible]	11	1	11	14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SY-AV	[illegible]	1	[illegible]	6	6	1	1	[illegible]	[illegible]	[illegible]	[illegible]
UA	[illegible]	14	[illegible]	[illegible]	[illegible]	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WSSAW	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WSFAA	[illegible]	5	7	[illegible]	[illegible]	7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FAA	[illegible]	54	41	[illegible]	[illegible]	14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WSSFE	[illegible]	11	[illegible]	[illegible]	[illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WSA	0	54	[illegible]	[illegible]	[illegible]	14	10	[illegible]	[illegible]	[illegible]	[illegible]
WSMO	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The combined SY-AV stations are in addition to the SYNOP and AVIAT [illegible]

The combined WSSAW and WSFAA stations have been included in [illegible] counts of the WS, SAWR, and FAA stations.

The FAA counts include FSS, TWR, CST, those AC and UA. It does not include the WSFAA.

The WSA counts include the WS stations located [illegible]

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RRT
ALABAMA											
ANNISTON	ANB/CALHOUN CO	04	ANB		33 35	085 51	0618	0	24 11 8		
AUBURN AG		10			32 35	085 30	0656	0			
BIRMINGHAM	MUNICIPAL	40	BHM	72228	33 34	086 45	0630	41	24 11 4	2	
CENTREVILLE		70	CKL		32 52	87 15		0			681
DOTHAN	MUNICIPAL	04	DHN		31 19	085 27	0351	0	24 11 8		
GADSDEN	MUNICIPAL	02	GAD		33 58	086 05	0564A	0	15 11		
HUNTSVILLE	HSV-MADISON CO	10	HSV		34 39	086 46	0644	0	24 11 8		X33
MOBILE	MOB BATES FIELD	10	MOB	72223	30 41	088 15	0221	41	24 11 4	2	X31
MONTGOMERY	DANNELLY	10	MGM	72226	32 18	086 24	0202	41	24 11 4	22	
MUSCLE SHOALS	MUNICIPAL	04	MSL		34 45	087 37	0562	0	24 11 8		
TUSCALOOSA	VAN DE GRAFF	04	TCL		33 14	087 37	0186	0	24 11 8		
ALASKA											
AMCHITKA	AIRPORT	02	AHT		51 23	179 15E	237	0	25		
ANCHORAGE	INTNL	70	ANC	70273	61 10	150 01	0132	41	24 11 8	222	
ANCHORAGE LAKE HOOD	LAKE HOOD SEAPLANE	05	LHD		61 11	149 57	144	0	09 11		
ANCHORAGE		40			61 13	149 57		0			
ANCHORAGE	MERRILL FIELD	04	MRI		61 13	149 50	0145A	0	24 11		
ANDREAFSKI	ST MARYS	02	AFK		62 04	163 18	0302A	0	03 21		
ANGOON		03	AGN		57 30	134 35	0035G	0	10 11		
ANIAK	AIRPORT	32	ANI	70232	61 35	159 32	0086	0	09 11 3		
ANNETTE	ANNETTE ISLAND	10	ANN	70398	55 02	131 34	0110	41	24 11 8	22	
ATTU		09	ATU	70409	52 50	173 11	0070G	0	09 41		
BARROW	W ROGERS W POST	10	BRW	70026	71 18	156 47	0013	41	24 11 8	22	
BARTER ISLAND	MUNICIPAL	10	BTI	70086	70 08	143 38	0050	41	24 11 8	22	
BETHEL	MUNICIPAL	10	BET	70219	60 47	161 48	0150	41	24 11 8	22	
BETTLES	AIRPORT	14	BTT	70174	66 55	151 31	0672	41	24 11 8		
BIG DELTA	AIRPORT	14	BIG	70267	64 00	145 44	1274	11	24 11 8		
CAPE DECISION	LGT STN	09	CDE	70388	56 00	134 08	0050	0	16 21 4		
CAPE HINCHINBROOK	LGT STN	09	CHO	70279	60 14	146 39	0185	0	05 21		
CAPE ST ELIAS	LGT STN	09	SCE	70360	59 48	144 36	0058	41	17 21 7		
CAPE SARICHEF	AIRPORT	09	CSH		54 36	164 56	0175	0	05 21		
CAPE SPENCER	LGT STN	09	CSP	70365	58 12	136 38	0088	41	16 21 8		
CIRCLE HOT SPRINGS	AIRPORT	02	CHP		65 29	144 36	0956A	0	25		
CLEAR	AIRPORT	02	SCR		64 18	149 11	0552A	0	12 21		
COLD BAY	AIRPORT	10	CDB	70316	55 12	162 43	0103	41	24 11 8	22	
COLLEGE	PHILLIPS FIELD	02			64 51	147 49	543	0	02 21		
CORDOVA	MILE 13	04	CDV		60 30	145 30	0048	0	24 11 8		
CRAIG		03	CGA	70392	55 29	133 09	0014	0	07 11		
DEADHORSE	AIRPORT	04	SCC		70 12	148 27	66	0	16 11		
DILLINGHAM	MUNICIPAL	04	DLG		59 03	158 31	0086A	0	09 11		

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RPT
ALASKA											
DRIFT RIVER	AIRPORT	02	DRF		60 35	152 09	30A	1	01 1		
DUTCH HARBOR	AIRPORT	02	DUT	70489	53 54	166 32	13A	0	04 41		
ELDRED ROCK	LGT STN	09	ERO	70364	58 59	135 13	0055	0	10 21		
FAIRBANKS	INTNL	10	FAI	70261	64 49	147 52	0454	41	24 11 8		22
FAREWELL	AIRPORT	14	FWL	70249	62 31	153 53	1503	0	09 12 3		
FIVE FINGER LS		09	FIV	70385	57 16	133 37	0035	0	10 21		
FORT YUKON	MUNICIPAL	03	FYU	70194	66 33	145 12	441	0	04 21 4		
FORT YUKON APT	MUNICIPAL	03	FYU		66 34	145 16	471	0	10 11		
GAMBELL	MUNICIPAL	02	GAM	70204	63 46	171 45	0025A	0	25		
GULKANA	INTERMEDIATE FD	14	GKN	70271	62 09	145 27	1579	41	24 11 4		
GUNSIGHT		13	GGN		61 54	147 19	2556A	0	03 21		
GUSTAVUS	AIRPORT	02	GST	70367	58 25	135 44	0020	0	05 21		
HOMER	MUNICIPAL	14	HOM	70341	59 39	151 30	0073	41	24 11 8		
ILIAMNA	INTERMEDIATE	04	ILI	70340	59 45	154 55	0160	0	04 11		
JUNEAU	MUNICIPAL	10	JNU	70381	58 22	134 35	0024	41	24 11 8		
KENAI	MUNICIPAL	04	ENA	70259	60 34	151 15	0095	0	24 11 8		
KETCHIKAN		14	KTN		55 21	131 40	08	0	11 11		
KING SALMON	AIRPORT	10	AKN	70326	58 41	156 39	0046	41	24 11 8		22
KOTZEBUE	RALPH WIEN	10	OTZ	70133	66 52	162 39	0016	41	24 11 8		22
LAKE CLARK		03	ZOO		60 17	154 17	271	0	16 11		
MANLEY HOT SPRINGS	AIRPORT	03	MLY		65 00	150 39	0270A	0	05 21		
MCGRATH	AIRPORT	10	MCG	70231	62 58	155 37	0338	41	24 11 4		22
MIDDLETON IS		11	MDO		59 26	146 20	0146	0	24 11		
MINCHUMINA	AIRPORT	01	MHM	70246	63 53	152 17	0701	0			
NENANA	MUNICIPAL	04	ENN	70260	64 33	149 05	0364	0	15 11 5		
NOME	AIRPORT	10	OME	70200	64 30	165 26	0022	41	24 11 8		22
NORTHWAY	AIRPORT	04	ORT	70291	62 57	141 56	1721	0	24 11 4		
NUNIVAK		14	SNV	70218	60 23	166 12	0050	0	04 21 4		
PALMER	MUNICIPAL	04	PAQ	70274	61 36	149 05	232	0	03 11 4		
PETERSBURG		07	PSG		56 49	132 57	[illegible]	0	10 11		
POINT RETREAT LS		09	ERT		58 25	134 57	0021	0	07 21		
PORT CLARENCE		09	KPC	70119	65 15	166 53	0018	0	05 21 4		
PORT HEIDEN	AIRPORT	03	PTH	70333	56 57	158 37	0045	0	05 21		
PRUDHOE BAY	AIRPORT	02	PUO		70 15	148 20	41	0	24 11 4		
PUNTILLA		03	PTI		62 06	152 45	1875	0	06 21		
QUINHAGAK	KWINHAGAK	[illegible]	UNH		59 45	161 54	[illegible]		25		
SAGWON		02	SAG		69 22	148 42	650	0	04 22		
ST PAUL IS	AIRPORT	10	SNP	70308	57 09	170 13	0024	41	24 11 8		22
SAND POINT	MUNICIPAL	02	SDP		55 20	160 30	0214	0	05 21		
SEWARD	MUNICIPAL	07	SWD	70277	60 07	149 27	0061	0	12 11		
SHEMYA	AIRPORT	10	SYA	70414	52 43	174 06	0102	41	24 11 8		22
SISTERS ISLAND		03	SSR		58 10	135 15	0066	0	03 11		
SITKA		04	SIT	70371	57 04	135 21	0067	0	24 11 4		

ELEVENTH EDITION

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RPT
ALASKA											

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FC	A	PWU	RPT
ALASKA													
SITKINAK		09	SKJ		56 33	154 09	0055	0	08	41			
SKAGWAY	MUNICIPAL	03	SGY	70362	59 28	135 19	0018	0	09	21			
SKWENTNA	AIRPORT	01	SKW	70255	61 58	151 12	0158	0	03	21			
SNOWSHOE LAKE		03	SSC		62 02	146 40	2410	0	03	11			
SUMMIT	AIRPORT	10	UMM	70264	63 20	149 08	2405	41	24	11	8		
TALKEETNA	AIRPORT	14	TKA	70251	62 18	150 06	0356	61	17	11	6		
TANANA	AIRPORT	04	TAL	70178	65 10	152 06	0225	0	16	11	5		
TOOKSOOK	AIRPORT	02	COK		60 32	165 07	00158	0					
TYONE LAKE		03	STO		62 31	146 42	2375	0	04	21			
UMIAT	AIRPORT	02	UMT		69 22	152 08	340	0	11	11			
UNALAKLEET	AIRPORT	14	UNK	70207	63 53	160 48	0021	41	24	11	8		
WALES	AIRPORT	02	WAA		65 37	168 03	0017	0	03	21			
WRANGELL		03	WRG	70387	56 28	132 23	0043	0	09	11			
YAKATAGA	INTERMEDIATE	03	CYT	70298	60 05	142 30	0026	0	04	22			
YAKUTAT	STATE	10	YAK	70361	59 31	139 40	0031	41	24	11	8	22	
ARIZONA													
DOUGLAS	BISBEE-DUG INTNL	04	DUG		31 27	109 36	4107	0	24	11	8		
FLAGSTAFF	PULLIAM	10	FLG	72375	35 08	111 40	7018	0	24	11	8		
GILA BEND		03	GBN		32 57	112 43	0723G	0	11	11	4		
GRAND CANYON	NATIONAL PARK	03	GCN	72378	35 57	112 09	6621	55	14	11	5		
LAKE HAVASU CITY	AIRPORT	02	LHU		34 27	114 22	G4905	0	01	92			
PAGE	AIRPORT	02	PGA		36 56	111 27	4310A	0	09	11			
PAYSON		03	PAS		34 14	111 20	4913G	0	07	21	2		
PHOENIX	SKY HARBOR MUN	10	PHX	72278	33 26	112 01	1107	41	24	11	4		
PRESCOTT	MUNICIPAL	04	PRC		34 39	112 26	5052	0	24	11	8		
SAFFORD	MUNICIPAL	03	SAD		32 51	109 38	3176A	0	05	21			
SHOW LOW		03	E03		34 15	110 02	6776G	0	07	21	2		
TUCSON	INTNL	10	TUS	72274	32 07	110 56	2555	41	24	11	4	122	
WINSLOW	MUNICIPAL	10	INW	72374	35 01	110 44	4883	41	24	11	4	222	
YUMA	INTNL	14	YUM	72280	32 40	114 36	0206	31	24	11	5	1	
ARKANSAS													
ELDORADO	MUNICIPAL	04	ELD		33 13	092 48	0285	0	24	11	8		
FAYETTEVILLE AG		10			36 04	094 10	1458G	0					
FAYETTEVILLE	DRAKE	04	FYV		36 00	094 10	1259	0	24	11	8		
FT SMITH	MUNICIPAL	10	FSM	72344	35 20	094 22	0463	41	24	11	4		K32
HARRISON	BOONE COUNTY	04	HRO		36 16	093 09	1365	0	24	11	8		
HOT SPRINGS	MEMORIAL	05	HOT		34 29	093 06	0535	0	16	11			

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWUL	RPT
ARKANSAS											
JONESBORO	MUNICIPAL	11	JBR		35 50	090 39	274	0	24 11 8		
KEISER AG		10			35 41	090 05	0232G	0			
LITTLE ROCK	ADAMS	10	LIT	72340	34 44	092 14	0265	41	24 11 4	222	581
PINE BLUFF	GRIDER FIELD	04	PBF		34 10	091 56	0214	0	24 11 8		
TEXARKANA	MUNICIPAL WEBB FIELD	06	TXK		33 27	094 00	0368	0	24 11 4		
CALIFORNIA											
ANAHEIM	HELIPORT	02	ANA		33 49	117 55	0140	0	05 21		
APPLE VALLEY	AIRPORT	02	APV		34 35	117 11	2960A	0	14 11		
ARCATA	AIRPORT	06	ACV		40 59	124 06	0225	0	24 11 8		
BAKERSFIELD	MEADOWS FIELD	14	BFL	72384	35 25	119 03	0492	41	24 11 4		
BEAUMONT		03	BUO		33 56	116 57	2600G	0	07 31 1		
BISHOP	AIRPORT	10	BIH	72480	37 22	118 22	4145	0	14 11 5	1	
BLUE CANYON	AIRPORT	71	BLU		39 17	120 42	5283	0	24 11 3		
BLYTHE	RIVERSIDE CO	04	BLH		33 37	114 43	0392	0	24 11 8		
BURBANK	HOLLYWOOD-BUR	05	BUR		34 12	118 22	775	0	24 11		
BURNEY		03	BNY		40 53	121 40	3141	0	01 31		
CAMPO		03	CZZ		32 37	116 28	2630G	0	06 21		
CARLSBAD	PALOMAR	03	CRQ		33 14	117 17	0328A	0	18 21		
CATALINA ISLAND	CATALINA	03	SXC		33 24	118 25	1580	0	04 21		
CHICO	MUNICIPAL	02	CIC	72497	39 48	121 51	0237A	0	15 11		
COLTON	AIRPARK	02			34 05	117 22	1100A	0	25		
CONCORD	BUCHANAN FD	03	CCR		37 59	122 03	0023	0	17 11		
CRESCENT CITY	MCNAMARA	04	CEC		41 47	124 14	0057	0	24 11 8		
DAGGETT	SAN BERNARDINO CO	04	DAG		34 52	116 47	1929	0	24 11 8		
EUREKA		10	EKA	72594	40 48	124 10	0060	41			X33
FARALLON ISLAND SE		09	FLI	72495	37 42	123 00	0030	41			
FORT BRAGG		07	FOB	72590	39 26	123 48	0074	41			
FRESNO	AIR TERMINAL	10	FAT	72389	36 46	119 43	0327	41	24 11 4	1	
FRESNO	CHANDLER MUN	05	FNC		36 44	119 49	0278A	0	17 11		
FULLERTON	MUNICIPAL	05	FUL		33 52	117 58	0096A	0	17 11		
HALF MOON BAY	HAF CO	02	HAF		37 31	122 30	0036A	0	25		
HAWTHORNE	MUNICIPAL	05	HHR		33 55	118 20	0063	0	17 11		
HAYWARD	AIR TERMINAL	05	HWD		37 39	122 07	0049A	0	13 11		
IMPERIAL	COUNTY	04	IPL		32 50	115 34	-048	0	24 11 8		
INYOKERN	KERN CO NO 4	02	IYK		35 40	117 50	2426	0	10 21		
LANCASTER	WM J FOX	02	WJF		34 45	118 13	2349A	0	15 11		
LAVERNE	BRACKETT FIELD	05	POC		34 06	117 47	1000A	0	16 11		
LONG BEACH	L BARRI-DAUGHERTY	10	LGB	72297	33 49	118 09	0040	0	24 11 8		
LONG BEACH PWR								0			
LOS ANGELES	INTNL	10	LAX	72295	33 56	118 24	0104	41	24 11 4		

ELEVENTH EDITION

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWL	RPT
CALIFORNIA											
		60			34 03	118 27	31CA	0			

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWL	RPT
CALIFORNIA													
LOS ANGELES		40			34 03	118 27	3108	0					
LOS ANGELES LS		09			33 47	118 15		0	04	51			
MARYSVILLE	YUBA CO	04	MYV		39 06	121 34	0073	0	24	11	8		
MERCED	MUNICIPAL	02	MCE		37 17	120 31	1538	0	06	11			
MODESTO	CITY-COUNTY	05	MOD		37 38	120 57	140	0	17	11			
MONTAGUE	SISKIYOU CO	04	SIY		41 47	122 28	2656	0	24	11	4		
MONTEREY	MRY PENINSULA	05	MRY		36 35	121 51	02208	0	06	11			
MT SHASTA		11	MHS	72595	41 19	122 19	3587	0	24	11	3		
MT WILSON		08	MWS	72249	34 14	118 04	5711	31	03	21	0		
NAPA	COUNTY	05	APC		38 13	122 17	56	0	17	11			
NEEDLES	MUNICIPAL	04	EED		34 46	114 37	0887	0	24	11	8		
OAKLAND UAU	INTNL	70	OAK	72493	37 45	122 13	0018	0				22	
OAKLAND	METROP OAK INTNL	14	OAK	72493	37 44	122 12	0007	0	24	11	8		
ONTARIO	INTERNATIONAL	04	ONT		34 03	117 37	0963	0	24	11	8		
OXNARD	VENTURA CO	05	OXR		34 12	119 12	00438	0	17	11			
PALMDALE	AIRPORT	04	PMD	72382	34 38	118 05	2538	0	24	11	8		
PALMDALE RADAR		10	PMD		34 36	118 05	25406	0					
PALM SPRINGS	MUNICIPAL	05	PSP		33 50	116 30	0480	0	17	11			
PALO ALTO	AIRPORT	05	PAO		37 24	122 07	028	0	17	11			
PASO ROBLES	COUNTY	04	PRB		35 40	120 38	0817	0	24	11	8		
PT ARENA		09	PAA	72493	38 57	123 44	0063	81					
PT ARGUELLO		09	PGU	72392	34 34	120 40	00760	82					
PT PIEDRAS BLANCAS		09	PPC	72396	35 40	121 17	0069	81					
POMONA AG		10			34 03	117 45	8636	0					
RED BLUFF	MUNICIPAL	14	RBL	72591	40 09	122 15	0353	81	24	11	5	1	
REDDING	MUNICIPAL	02	RDD		40 30	122 18	05008	0	17	11			
REDDING FW								0					
RIVERSIDE FW								0					
RIVERSIDE	MUNICIPAL	05	RAL		33 57	117 27	08163	0	17	11			
SACRAMENTO	METROPOLITAN	05	SMF		38 42	121 36	33	0	24	11			
SACRAMENTO RFC		60			38 35	121 30		0					
SACRAMENTO	EXECUTIVE	14	SAC	72483	38 31	121 30	0025	0	24	11	8		
SACRAMENTO		10			38 35	121 30	258	0					561
SALINAS	MUNICIPAL	04	SNS		36 40	121 36	0077	0	24	11	8		
SAN CARLOS	AIRPORT	05	SQL		37 31	122 15	28	0	17	11			
SANDBERG		71	SDB	72393	34 45	118 44	4523	25	24	11	3	1	
SAN DIEGO	BROWN	03	L63		32 34	116 59	510	0	12	11			
SAN DIEGO	GILLESPIE	03	SEE		32 49	116 58	03858	0	21	11			
SAN DIEGO	INTNL LINDBERGH F	10	SAN	72290	32 44	117 10	0028	0	24	11	8		
SAN DIEGO	MONTGOMERY	77	MYF	72290	32 49	117 08	0408	41				22	
SAN DIEGO	MONTGOMERY	03	GBP		32 49	117 09	04178	0	16	11			
SAN FRANCISCO SO		90			37 47	122 25	00526	0					
SAN FRANCISCO	INTNL	10	SFO	72494	37 37	122 23	0018	41	24	11	4		

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWU	RRT
CALIFORNIA													
SAN FRANCISCO WSFO		40	SFC		37 23	122 12	040	0					
SAN FRANCISCO PWF								0					
SAN FRANCISCO LS		09	ACS		37 45	122 42	0025	81					
SAN JOSE	MUNICIPAL	05	SJC		37 22	121 55	0056A	0	24	11			
SAN JOSE	REID/HILLVIEW	05	RHV		37 20	121 49	133A	0	17	11			
SAN LUIS OBISPO	COUNTY	02	SBP		35 14	120 39	208A	0	25				
SAN NICOLAS IS		40	NSI	72291	33 15	119 27	0571	0	15	21			
SANTA ANA	ORANGE CO	05	SNA		33 40	117 51	0052A	0	18	11			
SANTA BARBARA	MUNICIPAL	04	SBA		34 26	119 50	0020	0	24	11	4		
SANTA MARIA	SAN PUBLIC	10	SMX	72394	34 54	120 27	0238	21	17	11	3		
SANTA MONICA	MUNICIPAL	05	SMO		34 01	119 27	0175A	0	17	11			
SANTA ROSA	SONOMA CO	05	STS		38 31	122 49	148	0	17	11			
STOCKTON	METROPOLITAN	10	SCK	72492	37 54	121 15	0027	41	24	11	4		
SUSANVILLE	MUNICIPAL	08	SVE	72584	40 23	120 34	4196	71	07	21			
TAHOE CITY		09			39 11	120 07	6233G	0					
TAHOE VALLEY	LAKE TAHOE	05	TVL		38 54	120 00	6273	0	17	11	1		
THERMAL	AIRPORT	04	TRM		33 33	116 10	-112	0	24	11	4		
TORRANCE	MUNICIPAL	05	TOA		33 48	118 20	0101A	0	17	11			
TRUCKEE	TRUCKEE-TAHOE	03	TRK		39 19	120 08	5900G	0	05	21			
UKIAH	MUNICIPAL	04	UKI		39 08	123 12	0620	0	24	11	8		
VANDENBERG AFB		70	VBG	72393	34 45	120 34	0325	0				22	
VAN NUYS	AIRPORT	05	VNY		34 13	118 29	0799A	0	24	11			
VISALIA	MUNICIPAL	02	VIS		36 13	119 24	0292A	0	13	11			
COLORADO													
AKRON	WASHINGTON CO	04	AKO		40 10	103 13	4671	0	24	11	4		
ALAMOSA	AIRPORT	12	ALS	72462	37 27	105 52	7541	0	22	21	4	2	
ASPEN	SARDY FLD	03	ASE		39 13	106 52	7804	0	12	11			
BROOMFIELD	JEFFERSON COUNTY	05	BJC		39 54	105 07	5648A	0	17	11			
COLORADO SPRINGS	PETERSON FD	10	COS	72466	38 49	104 43	6170	0	24	11	4		
CORTEZ	MONTEZUMA CO	02	CEZ		37 18	108 38	5914A	0	15	11			
CRAIG		03	CAG	72571	40 31	107 31	6283	0	04	41	4		
DENVER SC		4			39 45	105 00	5292	0					
DENVER	STAPLETON INTNL	40	DEN	72469	39 46	104 52	5332	41	24	11	4	22	
DURANGO	DRO-LA PLATA CO	02	DRO		37 09	107 45	6684A	0	17	11			
DURANGO		03	4V5		37 11	107 45	6401	0	05	21			
EAGLE	COUNTY	04	EGE		39 39	106 55	6513	0	24	11	4		
FT COLLINS		03	FCL		40 35	105 05	5001G	0	17	11			
FRASER		03	FSR		39 57	105 50	8560G	0	12	11	4		
GRAND JUNCTION	MUNICIPAL	10	GJT	72476	39 07	108 32	4839	41	24	11	4	22	
GUNNISON	COUNTY	02	GUC		38 33	106 55	7667A	0	07	11			

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME AIRPORT NAME TYPE CALL NO. LAT. LONG. ELEV. SC AV FD A PWU RRT

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FC	A	PWU	RPT
COLORADO													
GUNNISON		03	2V9		38 33	106 56	7707	0	08	21	2		
HAYDEN	YAMPA VALLEY	02	HDN		40 30	107 15	6600G	0	08	11			
LA JUNTA	MUNICIPAL	04	LHX		38 03	103 31	4215	0	24	11	8		
LAMAR		03	4LJ	72463	38 07	102 36	3620	0	08	41	8		
LAMAR	MUNICIPAL	02	LAA		38 04	102 41	3703A	0	12	12			
LEADVILLE		03	LXV	72467	39 15	106 18	10159	0	08	41	8		
LIMON		70			39 11	103 42	5562	0	08	41	8		651
MONTROSE	COUNTY	02	MTJ		38 30	107 53	5759A	0	13	11			
MONTROSE		03	6V8		38 30	107 53	5747	0	05	21			
PUEBLO	MEMORIAL	10	PUB	72464	38 17	104 31	4720	41	24	11	4	2	
RIFLE		03	RIL		39 32	107 48	5400G	0	08	41			
SALIDA	HARRIET ALEXANDER	03	0V2		38 32	106 03	7488	0	12	31	4		
TRINIDAD	LAS ANIMAS CO	04	TAD		37 15	104 20	5743	0	24	11	8		
CONNECTICUT													
BRIDGEPORT	MUNICIPAL	10	BDR	72504	41 10	073 08	0017	41	24	11	4		
EAST HARTFORD	RENTSCHLER	32	EHT		41 45	072 37	0146A	0	17	11			
GROTON	TRUMBULL	32	GON		41 21	072 03	0020	0	16	12			
HARTFORD	BRADLEY FIELD	10	BDL	72508	41 56	072 41	0179	41	24	11	4	2	X34
HARTFORD RFC		60	HFDC					0					
MERIDEN	MRON-MARKHAM MUN	02	4B4		41 31	72 50	1028	0	03	21			
NEW HAVEN	TWEED NEW HAVEN	32	HVN		41 16	072 53	0017	0	13	11	7		
STORRS SC		40						0					
DELAWARE													
WILMINGTON	GREATER	10	ILG		39 40	075 36	0080	0	24	11	8		
FLORIDA													
APALACHICOLA		10	AQQ	72220	29 44	084 59	0035	0	08	41	8		561
CLEWISTON	MUNICIPAL	03	X53		26 44	080 57	0028	0	05	21	5		
CRESTVIEW	BOB SIKES	04	CEW		30 47	086 31	0185	0	24	11			
CROSS CITY	MUNICIPAL	01	CTY		29 38	083 06	0044	0	24	11			
DAYTONA BEACH	MUNICIPAL	10	DAB		29 11	081 03	0041	0	24	11	8		561
FT LAUDERDALE	FLL-HOLLYWD INTL	05	FLL		26 04	080 09	0010	0	24	11			
FT MYERS	PAGE FIELD	14	FMY	72210	26 35	081 52	0012	0	24	11	8		
GAINESVILLE	MUNICIPAL	14	GNV		29 41	082 16	0165	0	24	11	8		
HOLLYWOOD	NORTH PERRY	05	HWO		26 00	80 14	008	0	17	11			

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W E A T H E R   S E R V I C E   O F F I C E S   A N D   S T A T I O N S

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWL	RPT
FLORIDA													
JACKSONVILLE	CRAIG FIELD	04	CRG					0	24	11			
JACKSONVILLE	INTNL	05	JAX		30 30	81 42	294	0	24	11			
JACKSONVILLE	IMESON	10	IMF	72206	30 25	081 39	0031	41	24	11	4		
KEY WEST	INTNL	10	EYW	72201	24 33	081 45	0021	41	24	11	4		561
LAKELAND		10	LAL		28 02	081 57	0236	C	11	21			
LAKELAND SC		40						0					
MELBOURNE	CAPE KENNEDY REG	04	MLB		28 06	080 38	0027	0	24	11			
MIAMI		20	MIAC		25 43	080 17	0065	0					
MIAMI	INTNL	10	MIA	72202	25 48	080 16	0012	41	24	11	4	22	651
MIAMI	NEW TAMIAMI	04	TMB		25 39	080 26	0009A	0	24	11			
MIAMI	TRAINING TRANSITION	05	TNT		25 52	80 54	14A	0	11	11			
MIAMI	OPA LOCKA	05	OPF		25 54	80 17	09A	0	19	11			
OCALA	MUN JIM TAYLOR FD	32	OCF		29 10	082 14	0097	0	09	11			
ORLANDO	HERNDON	14	ORL	72205	28 33	081 20	0119	41	24	11	5		
PANAMA CITY	BAY CO	32	PFN		30 12	085 41	00209	0	19	11			
PENSACOLA	MUN HAGLER FLD	14	PNS		30 21	087 12	011A	0	24	11	8		
QUINCY AG		10			30 33	084 36	0245G	0					
ST PETERSBURG	ALBERT WHITTED	05	SPG		27 46	082 38	0006A	0	17	11			
ST PETERSBURG	PIE-CLEARWATER	04	PIE		27 55	082 41	0011A	C	24	11			
SARASOTA	BRADENTON	32	SRQ		27 24	082 33	0024A	0	20	11			
TALLAHASSEE	MUNICIPAL	10	TLH	72214	30 23	084 22	0068	41	24	11	4	4	
TAMPA	INTERNATIONAL	10	TPA	72211	27 58	082 32	0011	41	24	11	4	222	571
TITUSVILLE	TI-COCOA	02	TIX		28 31	80 48	35	0	19	11			
VERO BEACH	MUNICIPAL	04	VRB		27 39	080 25	0024	0	24	11	9		
WEST PALM BEACH	PALM BEACH INTNL	10	PBI		26 41	080 06	0021	0	24	11	8		
GEORGIA													
ALBANY	MUNICIPAL	04	ABY		31 32	084 11	0193	0	24	11			
ALMA	INTERMEDIATE	04	AMG		31 32	082 31	0206	0	17	11	6		
ATHENS	BEN EPPS FIELD	10	AHN	72311	33 57	083 19	0811	41	24	11	4	222	651
ATHENS SC		40			33 57	83 22		0					
ATLANTA REG		60			33 46	84 23		0					
ATLANTA	AIRPORT	40	ATL	72219	33 39	084 26	1034	41	24	11	4		
ATLANTA	FULTON CO	04	FTY		33 47	084 31	0844	0	24	11	1		
ATLANTA	DEKALB-PEACHTREE	05	PDK		33 53	084 18	1002A	0	16	11			
AUGUSTA	BUSH FIELD	10	AGS	72218	33 22	081 58	0148	41	24	11	4		
BRUNSWICK	MCKINNON	04	SSI		31 09	081 27	0024	0	24	11	8		
COLUMBUS	METROPOLITAN	15	CSG		32 31	084 56	0394	0	24	11	5		
EXPERIMENT AG		10			33 16	084 17	0925	0					
MACON	LEWIS B WILSON	10	MCN	72217	32 42	083 39	0362	41	24	11	4		
MACON FW					32 49	83 32	375	0					

W E A T H E R   S E R V I C E   O F F I C E S   A N D   S T A T I O N S

STATION NAME   AIRPORT NAME   TYPE   CALL   NO.   LAT.   LONG.   ELEV.   SC   AV FD A   PWL   RPT

GEORGIA

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWU	RPT
GEORGIA													
MOULTRIE	MGR-THOMASVILLE	02	MGR		31 05	083 49	02908	0	15	11			
ROME	RUSSELL FIELD	11	RMG		34 21	085 10	0643	0	24	12	4		
SAVANNAH	MUN APT TRAVIS F	10	SAV	72207	32 08	081 12	0051	41	24	11	4		
TIFTON AG		10			31 29	083 30		0					
VALDOSTA	MUNICIPAL	04	VLD		30 47	083 17	0223	0	24	11			
WAYCROSS	WARE CO	72	AYS	72213	31 15	082 24	152	0	25			222	651
HAWAII													
BARKING SANDS	AIRPORT	90	PHBK	91162	22 02	159 47	23	41	11	12		90	
FR FRIGATE SHOALS		09		91155	23 52	166 17	0006	81					
HAINA		07		91199	20 06	155 28	04606	22					
HANA	AIRPORT	03	PHHN		20 48	156 01	0085	0	04	11	1		
HANAPEPE		03		91163	21 55	159 35	00106	0	03	21	3		
HILO	LYMAN FIELD	10	PHTO	91285	19 43	155 04	0036	81	24	11	4	222	
HONOLULU	INTNL	40	PHNL	91182	21 20	157 55	0015	81	24	11	4	4	
HONOLULU RH								0					
KAANAPALI	AIRPORT	08	PHKP	91189	20 56	156 42	00086	41	10	11			
KAHULUI	AIRPORT	16	PHOG	91190	20 54	156 26	0067	51	24	11	3	3	
KAPOHO BEACH		03		91288	19 30	154 49	106	0	01				
KE-AHOLE	AIRPORT	06	PHKO		19 45	156 03	478	0	17	11			
KEALAKEKUA		07		91282	19 30	155 55	14506	12					
KEAWAKAPU BEACH		07		91191	20 42	156 27	00156	31					
KILAUEA POINT		09		91164	22 14	159 24	186	31					
KIOLAKAA-KEAA		03		91292	19 04	155 40	19606	0	03	11			
KOKEE		07		91161	22 09	159 39	42006	42					
LANAI CITY	AIRPORT	03	PHLY		20 49	156 57	13058	0	10	11	1		
LIHUE	AIRPORT	10	PHLI	91165	21 59	159 21	0148	81	24	11	4	222	
MAKAHUENA POINT		09		91166	21 52	159 27	00526	41					
MAKAPUU POINT		09		91193	21 19	157 39	0540	31					
MOLOKAI	AIRPORT	03	PHMK	91186	21 09	157 06	0451	0	11	11	4		
PUAKO		03		91197	19 59	155 50	13	0	04	21			
UPOLU POINT USCG LOR		09		91195	20 15	155 53	00616	41					
WAIALEE		07		91169	21 41	158 02	0038	41					
WAIMEA KOHALA	AIRPORT	03	PHMU		20 00	155 40	2670	0	09	11	3		
IDAHO													
BOISE	MUNICIPAL	40	BOI	72681	43 34	116 13	2868	41	24	11	4	122	
BOISE SC		80						0					
BURLEY	MUNICIPAL	04	BYI		42 32	113 46	4157	0	24	11	8		

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STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FC	A	PWU	RRT
IDAHO													
GOODING		08	GNG	72586	42 55	114 46	3668	51	11	11	1		
GRANGEVILLE	AIRPORT	07	S80	72687	45 55	116 06	3304	41	04	51			
HAILEY	FRIEDMAN MEM	02	SUN		43 30	114 18	5300G	0	10	11	1		
IDAHO FALLS	FANNING FIELD	04	IDA		43 31	112 04	4744	0	24	11	8		
LEWISTON	NEZ PERCE CO	12	LWS	72783	46 23	117 01	1436	31	13	11	3	1	
MALAD CITY	AIRPORT	04	MLC		42 10	112 19	4495	0	17	11	5		
MULLAN		04	MXN		47 28	115 46	3507	0	16	11	5		
MULLAN		03	SO6		47 23	115 49	3310	0	03	21	3		
POCATELLO	MUNICIPAL	10	PIH	72578	42 55	112 36	4478	41	24	11	4		
SALMON	MUNICIPAL	07	SMN	72686	45 07	113 53	4055	61	05	21	0		
STREVELL		03	4SV		42 01	113 15	5290G	0	06	21	3		
TWIN FALLS	JOSLIN	02	TWF		42 29	114 29	4148	0	13	91			
TWIN FALLS AG		10			42 33	114 21	3922G	0					
ILLINOIS													
ALTON	CIVIC MEMORIAL	05	ALN		38 53	090 03	5442	0	17	11			
BLOOMINGTON	MUNICIPAL	02	BMI		40 29	088 57	0875	0	23	11			
BRADFORD	RINKENBERGER	01	BDF		41 14	089 37	0803	0	24	11			
CAIRO		10	CIR		37 03	089 10	0357	0					
CARBONDALE	SOU ILL	02	MDH		37 47	089 15	0416	0	13	11			
CHAMPAIGN	U OF ILL	05	CMI		40 02	088 17	0763	0	24	11			
CHAMPAIGN SC		90						0					
CHICAGO	DUNNE CRIB	07	DUK		41 47	087 32	0579G	32					
CHICAGO DUPAGE	DUPAGE CO	04	DPA		41 55	088 15	767	0	24	11			
CHICAGO	MEIGS	05	CGX		41 52	087 37	0592A	0	17	11			
CHICAGO	MIDWAY	10	MDW	72534	41 47	087 45	0623	41	24	11	4	2	
CHICAGO	OHARE INTNL	10	ORD	72530	41 59	087 54	0674	0	24	11	9		
CHICAGO WSFO		40	CHIF		41 47	087 36	0594G	0					
CHICAGO		70			41 47	87 36	594G	0					
DANVILLE	VERMILION CO	02	DNV		40 12	087 36	0695A	0	25				571
DECATUR	AIRPORT	32	DEC		39 50	088 52	0679A	0	20	11			
DIXON	WALGREEN FIELD	02	C77		41 50	89 27	786A	0	25				
ELGIN	AIRPORT	02	C06		42 04	88 17	790A	0	25				
GALESBURG	MUNICIPAL	02	GBG		40 56	090 26	0762A	0	15	11			
JOLIET RC								0					
KANKAKEE	GREATER KANKAKEE	02	3KK		41 04	87 51	623A	0	14	11			
MACOMB	MUNICIPAL	02	MQB		40 31	90 38	703A	0	25				
MARION	WILLIAMSON CO	02	MWA		37 45	089 01	0472A	0	17	11			
MATTOON	COLES CO MEM	02	MTO		39 29	088 17	0721A	0	16	11			
MOLINE	QUAD CITY	10	MLI	72544	41 27	090 31	0594	41	24	11	4	2	
MT VERNON	MT VN-OUTLAND	02	MVN		38 19	088 52	479A	0	16	11			

STATION NAME AIRPORT NAME TYPE CALL NO. LAT. LONG. ELEV. SC AV FC A PWU RRT

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FC	A	PWU	RRT
ILLINOIS													
OLNEY	OLNEY NOBLE	02	OLY		38 43	88 10	470A	0	25				
PEORIA	GREATER PEORIA	10	PIA	72532	40 40	089 41	0662	41	24	11	4	22	
QUINCY	BALDWIN FLD	04	UIN		39 56	091 12	0766	0	24	11	8		
ROCKFORD	GREATER RFD	10	RFD	72543	42 12	089 06	0743	0	24	11	8		
SALEM	SALEM LECKRONE	70	SLO	72433	38 39	88 58	581	61				22	
SPRINGFIELD	CAPITAL	10	SPI	72439	39 50	089 40	0613	41	24	11	4		
STERLING-ROCK FALLS	WHITESIDE COUNTY	02	SQI		41 44	089 41	0645A	0	15	11			
VANDALIA	MUNICIPAL	04	VLA		38 59	089 10	0540	0	24	11	8		
INDIANA													
ANDERSON	MUNICIPAL	02	AID		40 06	85 37	913A	0	25				
BLOOMINGTON	MONROE CO MUN	02	BMG		39 08	086 37	847A	0	14	11			
ELKHART	MUNICIPAL	02	3EK		41 43	85 59	779A	0	25				
EVANSVILLE	DRESS MEMORIAL	10	EVV	72432	38 03	087 32	0388	41	24	11	4	2	561
FT WAYNE	MUN BAER FIELD	10	FWA	72533	41 00	085 12	0828	41	24	11	4	2	X34
GARY	MUNICIPAL	02	GYY		41 37	87 25	616	0	25				
INDIANAPOLIS	MUN-WEIR COOK	40	IND	72438	39 44	086 17	0808	41	24	11	4	2	X34
KOKOMO	MUNICIPAL	02	OKK		40 32	086 04	0827A	0	25				
LAFAYETTE SC		80						0					
MARION	MUNICIPAL	02	MZZ		40 29	085 41	0858A	0	25				
MICHIGAN CITY	JOE PHILLIPS	02	MGC		41 42	86 49	650A	0	25				
MICHIGAN CITY		09			41 43	86 54	579G	42					
MUNCIE	DEL CO JOHNSON FD	32	MIE		40 14	085 23	0947	0	19	11			
PLYMOUTH	MUNICIPAL	02	C65		41 22	86 18	796A	0	25				
SOUTH BEND	ST JOSEPH CO	10	SBN	72535	41 42	086 19	0773	41	24	11	4		
TERRE HAUTE	HULMAN	04	HUF		39 27	087 18	0593	0	24	11			
VALPARAISO	PORTER COUNTY MUN	02	VPZ		41 27	87 03	768A	0	25				
WARSAW	MUNICIPAL	02			41 17	85 51	842A	0	25				
W LAFAYETTE	PURDUE U	04	LAF		40 25	086 56	0637	0	24	11	8		
WEST LAFAYETTE AC		10			40 28	87 00		0					
IOWA													
BURLINGTON	MUNICIPAL	04	BRL		40 47	091 07	0702	0	24	11			
CARROLL	ARTHUR N NEU	02	CIN		42 03	094 47	1202A	0	25				
CEDAR RAPIDS	MUNICIPAL	04	CID		41 53	091 42	0871	0	24	11	8		
CLINTON	MUNICIPAL	02	CWI		41 50	90 20	707A	0	15	11			
DAVENPORT	MUNICIPAL	02	DVN		41 37	90 36	753A	0	25				
DECORAH	MUNICIPAL	02	DEH		42 17	91 45	1154A	0	25				
DES MOINES	MUNICIPAL	10	DSM	72546	41 32	093 39	0963	41	24	11	4	1	561

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PNU	RRT
IOWA											
DES MOINES SC		80			41 35	093 37	0800G	0			
DUBUQUE	MUNICIPAL	12	DBQ	72547	42 24	090 42	1080	31	16 11 3		
FORT DODGE	MUNICIPAL	02	FOD		42 33	094 11	1162A	0	25		
FORT MADISON	MUNICIPAL	02	K27		40 40	91 20	724A	0	25		
KEOKUK	MUNICIPAL	02			40 28	91 26	670A	0	25		
LAMONI		03	3OI		40 37	093 56	1122	0	16 61 8		
MARSHALLTOWN	MUNICIPAL	02	MIW		42 07	92 55	974A	0	25		
MASON CITY	MUNICIPAL	04	MCW		43 09	093 20	1225	0	24 11 8		
OTTUMWA	INDUSTRIAL	04	OTM		41 06	092 27	0950	0	24 11		
SHELDON	MUNICIPAL	02	SHL		43 13	95 50	1419A	0	25		
SHENANDOAH	MUNICIPAL	02	SDA		40 45	95 25	952	0	25		
SIOUX CITY	MUNICIPAL	10	SUX	72557	42 24	096 23	1103	41	24 11 4	1	
SPENCER		07	3SE	72650	43 10	095 09	1339	71	19 11 0		
SPENCER	MUNICIPAL	02	SPW		43 10	95 12	1335A	0	25		
WATERLOO	MUNICIPAL	10	ALO	72548	42 33	092 24	0878	0	24 11 8		
KANSAS											
CHANUTE	MUNICIPAL	04	CNU		37 40	095 29	1011	0	24 11 8		
COLBY	MUNICIPAL	02	CBK		39 25	101 03	3179A	0	25		
CONCORDIA	BLOSSER MUN	10	CNK	72458	39 33	097 39	1484	41	24 11 4		XM2
DODGE CITY	MUNICIPAL	10	DDC	72451	37 46	099 58	2592	41	24 11 4	222	X34
EMPORIA	MUNICIPAL	04	EMP		38 20	096 12	1212	0	24 11 8		
FORT SCOTT	MUNICIPAL	02	K67		37 43	94 46	916A	0	25		
GARDEN CITY	MUNICIPAL	04	GCK		37 56	100 43	2882	0	24 11 8		
GARDEN CITY		70						0			
GOODLAND	RENNER FLD	10	GLD	72465	39 22	101 42	3688	41	24 11 4	2	X32
GREAT BEND	MUNICIPAL	02	GBD		38 21	098 52	1890A	0	25		
HAYS	MUNICIPAL	02	HYS		38 51	099 16	1998A	0	25		
HILL CITY	MUNICIPAL	04	HLC		39 23	099 50	2221	0	24 11 8		
HUTCHINSON	MUNICIPAL	05	HUT		38 04	097 52	1524	0	24 11		
INDEPENDENCE	MUNICIPAL	02	IDP		37 09	95 47	826A	0	25		
KANSAS CITY	FAIRFAX	05	KCK		39 09	094 35	746A	0	25		
LIBERAL	MUNICIPAL	02	LBL		37 03	100 58	2888	0	25		
MANHATTAN SC		80						0			
MANHATTAN	MUNICIPAL	32	MHK		39 09	096 40	1070	0	16 11		
NEWTON	CITY-COUNTY	02	EWK		38 03	97 17	1528A	0	03 21		
OLATHE	JOHNSON COUNTY	02	OJC		38 51	94 44	1096A	0	25		
PARSONS	TRI CITY	02	PPF		37 20	095 30	0899A	0	14 11		
RUSSELL	MUNICIPAL	04	RSL		38 52	098 49	1869	0	24 11 8		
SALINA	MUNICIPAL	04	SLN		38 48	97 39	1282	0	24 11 8		
TOPEKA	MUNICIPAL	10	TOP	72456	39 04	095 38	0885	41	24 11 4	22	X34
WICHITA	MUNICIPAL	10	ICT	72450	37 39	097 25	1340	41	24 11 4	2	571

ELEVENTH EDITION

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RRT
KENTUCKY											
BOWLING GREEN	CITY COUNTY	04	BWG		36 58	086 26	0536	0	24 11 8		
LEXINGTON	BLU GRASS FIELD	10	LEX	72422	38 02	084 36	0989	41	24 11 4		
LEXINGTON AG		10			38 01	084 31	1059G	0			
LONDON	CORBIN LOZ MAP M	04	LOZ		37 05	084 05	1211	0	24 11 8		
LOUISVILLE	BOWMAN FIELD	04	LOU		38 14	85 40	556	0	24 11		
LOUISVILLE	STANDIFORD FIELD	10	SDF	72423	38 11	085 44	0488	41	24 11 4	2	X34
OWENSBORO	DAVIESS CO	32	OWB		37 45	087 10	417	0	19 11		
PADUCAH	BARKLEY	04	PAH		37 04	088 46	0413	0	24 11		
PIKEVILLE		08	PKV	72413	37 29	082 31	0700	31	07 21 2		
LOUISIANA											
ALEXANDRIA	ESLER FIELD	14	ESF		31 23	092 18	0118	0	24 11 8		
BATON ROUGE	RYAN MUN	10	BTR	72230	30 32	091 09	0076	0	24 11 8		X13
BATON ROUGE SC		90			30 25	91 11		0			
BOOTHVILLE		70	BVE	72232	29 20	089 24	0002	0			
FORT POLK	USA AIRFIELD	02	POE		31 03	093 11	0330A	0	17 12		
LAFAYETTE	MUNICIPAL	04	LFT		30 12	091 59	0042	0	24 11 8		
LAKE CHARLES	MUNICIPAL	10	LCH	72240	30 07	093 13	0032	41	24 11 4	222	561
MONROE	MUNICIPAL	04	MLU		32 31	092 03	0081	0	24 11 8		
NEW IBERIA	ACADIANA REGIONAL	02	1R3					0	25		
NEW ORLEANS	INTNL/MOISANT FLD	10	MSY	72231	29 59	090 15	0030	41	24 11 4		
NEW ORLEANS WSFO		40	MSYC		29 57	090 05	0177	0			561
NEW ORLEANS	LAKEFRONT	04	NEW		30 02	090 02	10A	0	24 11		
SHREVEPORT	MUNICIPAL	10	SHV	72248	32 28	093 49	0259	41	24 11 4	222	X13
SHREVEPORT	DOWNTOWN	05	DTN		32 32	093 45	0179A	0	16 11		
MAINE											
AUBURN	LEWISTON MUN	02	LEW		44 03	070 17	271A	0	13 11		
AUGUSTA	STATE	04	AUG		44 19	069 48	0360	0	24 11 8		
BAR HARBOR	AIRPORT	02	BHB		44 27	068 22	0084A	0	08 11		XX1
BRUNSWICK		70	NHZ	74392	43 54	69 56	72G	0			
CARIBOU	MUNICIPAL	10	CAR	72712	46 52	068 01	0628	31	17 11 3	122	
EASTPORT		07		72608	44 55	067 00	0075	31			
GREENVILLE		03	3B1		45 28	069 35	1041	0	06 21 6		

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RPT
MAINE											
HOULTON	INTNL	04	HUL		46 04	067 47	0476	0	24 11 8		
MILLINOCKET	MUNICIPAL	04	MLT		45 39	068 41	0413	0	24 11 8		
OLD TOWN	MUNICIPAL	04	OLD		44 57	068 40	0124	0	24 11 8		
PORTLAND LS		09		74393	43 32	070 06		7			
PORTLAND	INTNL JETPORT	70	PWM	72606	43 39	070 19	0063	41	24 11 4	22	
PRESQUE ISLE	MUNICIPAL	02	PQI		46 42	068 03	0534A	0	17 11		
ROCKLAND	KNOX COUNTY	02	RKD		44 04	069 06	0060A	0	3 11		
RUMFORD		07	RUM	72618	44 32	070 32	0674	41			
WATERVILLE	LAFLEUR	02	WVL		44 32	69 41	3319	0	02 21		
MARYLAND											
ABERDEEN	PHILLIPS AAF	02	APG		39 28	76 10	0057	0			
BALTIMORE	FRIENDSHIP INTL	12	BAL	72406	39 11	076 40	0156	41	24 11 4		
COLLEGE PARK		80						0			
HAGERSTOWN	MUNICIPAL	02	HGR		39 42	077 43	0704A	0	09 11		
OCEAN CITY		09		74595	38 23	075 05	017	41			
PATUXENT RIVER		70	NHK					0			
SALISBURY	WICOMICO CO	04	SBY		38 20	075 30	0060	0	24 11 4		XX
MASSACHUSETTS											
BOSTON LS		39	NRC		42 20	070 44	0020	72			
BOSTON	LOGAN INTNL	40	BOS	72509	42 22	071 02	0020	41	24 11 4	?	KM4
BOSTON SWP								2			
BOSTON [illegible]		80						0			
CHATHAM		7	CHH	74494	41 40	69 58	44	41		22	
HYANNIS	BARNSTABLE MUN AIRPORT	15	HYA		41 40	070 17	0052A	0	17 11 4		
MARTHAS VINEYARD		12	MVY		41 24	070 36	0068A	0	11 11		
NANTUCKET LS		09		74497	40 33	069 24	0016	42			
NANTUCKET	MEMORIAL	05	ACK		41 15	070 04	0012	0	24 11		
NEW BEDFORD	MUNICIPAL	15	EWB		41 41	070 57	0079	0	17 11		
NORWOOD	MUNICIPAL	15	OWD		42 11	71 11	50A	0	17 11		
PITTSFIELD LS	MUNICIPAL	12	PSF		42 26	073 14	1166	0	25		
PITTSFIELD		07	PSF					0			
WESTFIELD	BARNES MUN	05	BAF		42 10	072 43	0027	0	24 11		
WORCESTER	MUNICIPAL	11	ORH		42 16	071 52	1017	0	24 11 6		914

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RPT

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWL	RRT
MICHIGAN													
ALLEGAN	PADGHAM FIELD	02	35D		42 32	85 49	695	0	25				
ALMA	GRATIOT MUNICIPAL	02	AMN		43 19	84 41	754A	0	25				
ALPENA	PHELPS COLLINS FD	10	APN	72639	45 04	083 34	0693	41	24	11	4	1	
BATTLE CREEK	KELLOGG	05	BTL		42 18	085 14	0939	0	24	11			
BAY CITY LS		09		72673	43 38	083 51	0581G	44					
BELLAIRE	ANTRIM COUNTY	02	ACB		44 59	85 12	640	0	25				
BELLE ISLE LS		09		72742	42 20	082 58	580G	44					
BENTON HARBOR	ROSS	02	BEH		42 08	086 26	643A	0	16	11			
DETROIT	WILLOW RUN	05	YIP		42 14	083 32	0777	0	24	11			
DETROIT	METROPOLITAN	40	DTW	72537	42 14	083 20	0664	41	24	11	4		561
DETROIT	CITY	04	DET		42 25	083 01	0626	0	24	11			
DEVILS IS LS		09	3DI		47 05	90 44	629G	44					
EAGLE HARBOR LS		09	EGH		47 28	088 10	0607G	42					
EAST LANSING AG		10						0					
ESCANABA		07		72648	45 45	087 03	0612	61					
ESCANABA	MUNICIPAL	02	ESC		45 44	087 05	608A	0	15	11			
FLINT	BISHOP	10	FNT	72637	42 58	083 44	0766	41	24	11	4	322	X34
GRAND MARAIS		09	3GR		46 41	85 59	600G	42					
GRAND RAPIDS	KENT CO	10	GRR	72635	42 53	085 31	0803	41	24	11	4		
HANCOCK/PORTAGE LS		09	HOK		47 14	088 38	0624G	44					
HARBOR BEACH		09		72743	43 51	082 39	0581G	44					
HOLLAND	PARK TOWNSHIP	02	HLM		42 48	86 10	612	0	25				
HOLLAND	TULIP CITY	02	C19		42 45	86 07	680A	0	25				
HOUGHTON	COUNTY	04	CMX		47 10	088 30	1070	0	24	11	8		
HOUGHTON LAKE	ROSCOMMON CO	10	HTL	72638	44 22	084 41	1161	41	24	11	4		
IRON MOUNTAIN	FORD	02	IMT		45 49	088 07	1170A	0	15	11			
IRONWOOD	GOGEBIC CO	02	IWD		46 32	090 08	1248A	0	16	11			
JACKSON	REYNOLDS	04	JXN		42 16	084 28	1020	0	24	11	8		
KALAMAZOO	MUNICIPAL	32	AZO		42 14	085 33	0874A	0	19	11			
LANSING	CAPITAL CITY	10	LAN	72539	42 47	084 36	0874	0	24	11	8		
LANSING SHOAL LIGHT		09		737	45 54	085 34	0580G	44					
LUDINGTON	MASON COUNTY	02			43 58	86 25	642A	0	25				
LUDINGTON		09			43 57	86 28	597G	44					
MANISTEE	MBL-BLACKER	02	MBL		44 16	086 15	0615A	0	16	11			
MANISTIQUE	SCHOOLCRAFT COUNTY	02	ISQ		45 59	86 11	684A	0	25				
MANITOU ISLAND LS		09		774	47 25	087 35	0609G	44					
MARQUETTE	MQT COUNTY	04	MQT		46 32	087 34	1425	0	24	11	8		
MARQUETTE		10		72743	46 34	087 24	0734	31				1	
MARQUETTE LS		09	3MQ		46 33	087 23	0644G	44					
MENOMINEE	COUNTY	02	MNM		45 07	087 38	0621A	0	16	11			
MUSKEGON	COUNTY	10	MKG	72636	43 10	086 14	0633	41	24	11	4	2	X34
MUSKEGON LS		09	MKM		43 14	086 20	0598G	44					
PASSAGE ISLAND LS		09		774	48 13	088 22	0656G	42					
PELLSTON	EMMETT CO	04	PLN		45 34	084 48	0715	0	24	11	8		

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RRT
MICHIGAN											
PT BETSIE LS		09		637	44 42	086 15	0597G	44			
PONTIAC	OAKLAND-PONTIAC	05	PTK		42 40	83 25	980A	0	16 11		
PORT HURON	FORT GRATIOT	09		72763	43 00	082 25	0581G	44			
ROCK OF AGES LS		04	3RA		47 52	089 19	0602G	44			
SAGINAW	TRI CITY	04	MBS		43 32	084 05	0670	0	24 11 4		
ST IGNACE		09	3IG		45 47	84 43	579G	42			
ST JOSEPH LGS		09		573	42 07	086 29	0579G	44			
SAULT STE MARIE	MUNICIPAL	14	SSM	72734	46 28	084 22	0724	41	24 11 4	22	
TAWAS POINT		09	TPT		44 15	083 26	0583G	44			
THUNDER BAY IS LS		09	TBI		45 02	083 12	0583G	44			
TRAVERSE CITY	MUNICIPAL	04	TVC		44 44	085 35	0630	0	24 11 4		
WHITEFISH POINT		07	WFP	773	46 45	84 59	610G	44			
MINNESOTA											
ALEXANDRIA	MUNICIPAL	04	AXN		45 52	095 23	1431	0	24 11 4		
BAUDETTE	MUNICIPAL	02	BDE		48 43	094 36	1083A	0	11 11		
BEMIDJI	MUNICIPAL	07	BJI	72755	47 30	094 56	1377	41	18 11 0		
BRAINERD	CROW WING CO	02	BRD		46 24	094 08	1226A	0	16 11		
DETROIT LAKES	MUNICIPAL	02	DTL		46 50	95 53	1396A	0	25		
DULUTH	INTNL	10	DLH	72745	46 50	092 11	1417	41	24 11 4	1	
DULUTH HARBOR STA		09	3DH		46 46	92 05	610G	41			
FAIRMONT	MUNICIPAL	02	FRM		43 39	094 25	1161A	0	14 11		
HIBBING	CHISHOLM HIBBING	04	HIB		47 23	092 51	1357	0	24 11 4		
INTERNATIONAL FALLS	FALLS INTNL	10	INL	72747	48 34	093 23	1183	41	24 11 4	22	
MANKATO	MUNICIPAL	02	MKT		44 13	093 55	1020A	0	14 11		
MINNEAPOLIS	MSP-ST PAUL INTNL	40	MSP	72658	44 53	093 13	0838	41	24 11 4		561
MINNEAPOLIS	FLYING CLOUD	05	FCM		44 50	093 27	0905A	0	17 11		
MINNEAPOLIS	CRYSTAL	05	MIC		45 04	093 21	0869A	0	16 11		
NORTH SUPERIOR		09	3NS		47 44	90 20		44			
PARK RAPIDS	MUNICIPAL	02	PKD		46 54	095 04	1450	0	25		
REDWOOD FALLS	MUNICIPAL	04	RWF		44 33	095 05	1030	0	24 11 4		
ROCHESTER	MUNICIPAL	10	RST	72644	43 55	092 30	1320	41	24 11 4		K34
ST CLOUD	WHITNEY MEM	11	STC	72655	45 35	094 11	1043	31	14 11 3	122	
ST PAUL	DOWNTOWN	05	STP		44 56	093 04	0703A	0	16 11		
ST PAUL SC		40			44 54	093 10	1010G	0			
THIEF RIVER FALLS	MUNICIPAL	02	TVF		48 04	096 11	1116A	0	17 11		
WILLMAR	MUNICIPAL	02	ILL		45 07	95 05	1130A	0	25		
WINDOM	MUNICIPAL	02	MWM		43 55	95 07	1409A	0	25		
WINONA	MUN-MAX CONRAD	02	ONA		44 05	091 47	0656A	0	16 12		
WORTHINGTON	MUNICIPAL	02	OTG		43 39	095 35	1574A	0	16 11		

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RRT
MISSISSIPPI											
COLUMBUS	LOWNDES CO	02	LBS		33 28	088 23	0188A	0	15 11		
	AFB	02	GLH		33 29	090 59	0131G	0	12 11		

WORTHINGTON MUNICIPAL 02 OTG 43 39 095 35 1574A 0 16 11

W E A T H E R S E R V I C E O F F I C E S A N D S T A T I O N S

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWUL	RRT
MISSISSIPPI													
COLUMBUS	LOWNDES CO	02	LBS		33 28	088 23	0188A	0	15	11			
GREENVILLE	AFB	02	GLH		33 29	090 59	01316	0	12	11			
GREENWOOD	GRNWD-LEFLORE	04	GWO		33 30	090 05	0154A	0	24	11	8		
GULFPORT	MUNICIPAL	32	GPT		30 24	089 04	0028A	0	18	11			
HATTIESBURG	MUNICIPAL	02	HBG		31 16	089 15	0151A	0	12	11			
JACKSON	THOMPSON FLD MUN	10	JAN	72235	32 19	090 05	0331	41	24	11	4	222	651
LAUREL	MUNICIPAL	02	LUL		31 40	089 10	0238A	0	12	11			
MCCOMB	PIKE CO	04	MCB		31 15	090 28	0468	0	24	11	9		
MERIDIAN	KEY FIELD	10	MEI	72234	32 20	088 45	0310	41	24	11	4		X33
MISS TEST FACILITY		70	MTF	74768	30 22	89 35	31	0				22	
NATCHEZ	HARDY-ANDERS	02	HEZ		31 37	091 15	0272A	0	15	11			
OXFORD	UNIVERSITY	02	UOX		34 23	089 33	04511	0	14	11			
PASCAGOULA	JACKSON CO	02	PGL		30 23	088 30	0016A	0	12	19			
STONEVILLE AG		10			33 25	090 55		0					
TUPELO	MUNICIPAL	02	TUP		34 16	088 46	0361A	0	16	11			
MISSOURI													
CAPE GIRARDEAU	MUNICIPAL	04	CGI		37 14	089 35	0352	0	24	11	9		
COLUMBIA SC		90						0					
COLUMBIA	REGIONAL	10	COU	72445	38 49	92 13	898	41	24	11	4	2	X34
JEFFERSON CITY	MEMORIAL	02	JEF		38 36	092 10	0547A	0	25				
JOPLIN	MUNICIPAL	04	JLN		37 10	094 30	0985	0	24	11	9		
KAISER	LEE C FINE MEM	02	AIZ		38 06	92 33	869	0	25				
KANSAS CITY RFC		60						0					
KANSAS CITY NSSFC		20			39 06	094 35	1355	0					561
KANSAS CITY	INTNL	05	MCI		39 19	094 43	1033	0	24	11			
KANSAS CITY	MUNICIPAL	10	MKC	72446	39 07	094 36	0750	41	24	11	4		
KANSAS CITY SCHOOL								0					
KANSAS CITY PH								0					
KIRKSVILLE	C CANNON MEM	04	IRK		40 05	092 33	0966	0	24	11	9		
MONETT		70	UMN	72349	36 53	93 54	1435	0	06	21	6	22	651
POPLAR BLUFF	EARL FIELDS MEMORIAL	02	M15		36 46	90 19	330A	0	25				
PORTAGEVILLE AG		10			36 25	089 42	2846	0					
ST JOSEPH	ROSECRANS MEM	05	STJ	72449	39 46	094 55	0818	0	24	11			
ST LOUIS		70			38 37	90 11	4496	0				2	
ST LOUIS	LAMBERT	40	STL	72434	38 45	090 23	0564	41	24	11	4	2	571
SEDALIA	MEMORIAL	02	DMC		38 42	93 11	909A	0	25				
SIDNEY	SDY-RICHMOND MUN	02	SDY		47 43	104 11	1970A		25				
SPIRIT OF ST LOUIS	AIRPORT	02	2KC		38 39	090 38	0462A	0	16	11			
SPRINGFIELD	MUNICIPAL	10	SGF	72440	37 14	093 23	1270	41	24	11	4	2	
VICHY	ROLLA NATIONAL	04	VIH		38 08	091 46	1137	0	24	11			
WEST PLAINS		07	H63	72344	36 44	091 51	1111	41					

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W E A T H E R   S E R V I C E   O F F I C E S   A N D   S T A T I O N S

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FC A	PWL	RRT
MONTANA											
BILLINGS	LOGAN FIELD	10	BIL	72677	45 48	108 32	3570	41	24 11 4	1	
BOZEMAN	GALLATIN FIELD	04	BZN		45 47	111 09	4444	0	24 11 5		
BROADUS		07	4BC	72667	45 26	105 24	3032	41	04 51 0		
BUTTE	SILVER BOW CO	04	BTM		45 57	112 30	5533	0	24 11 8		
CUTBANK	MUNICIPAL	04	CTB		48 36	112 22	3838	0	24 11 4		
DILLON	BEAVERHEAD CO	04	DLN		45 15	112 33	5209	0	24 11 8		
DRUMMOND		03	3DU		46 40	113 09	3942G	0	13 11 5		
ELLISTON		03	ETH		46 34	112 26	5075	0	03 21		
GLASGOW	INTNL	10	GGW	72768	48 13	106 37	2298	41	24 11 4	22	
GLENDIVE	DAWSON COMMUNITY	02	GDV		47 08	104 48	2476A	0	25		
GREAT FALLS	INTNL	40	GTF	72775	47 29	111 22	3657	41	24 11 4	22	
HARLOWTON		03	3HT		46 26	109 50	4161G	0	06 21		
HAVRE	CITY COUNTY	10	HVR	72777	48 33	109 46	2595	41	24 11 4	2	
HELENA	AIRPORT	10	HLN	72772	46 36	112 00	3898	41	24 11 4		
KALISPELL	GLACIER PARK INTNL	10	FCA	72779	48 18	114 16	2973	41	24 11 4		
LEWISTOWN	MUNICIPAL	04	LWT		47 03	109 27	4146	0	24 11 8		
LIVINGSTON	MISSION	04	LVM		45 42	110 26	4618	0	24 11 8		
MILES CITY	MUNICIPAL	04	MLS		46 26	105 52	2634	0	24 11 4		
MISSOULA	JOHNSON*BELL FIELD	10	MSO	72773	46 55	114 05	3189	41	24 11 4	1	561
MONIDA		03	MQM		44 34	112 19	6785G	0	10 21		
THOMPSON FALLS		03	3TH		47 36	115 22	2380G	0	06 21		
WEST YELLOWSTONE		07	WEY	72676	44 39	111 06	6669	41	03 41		
WEST YELLOWSTONE	YELLOWSTONE	02	WYS		44 41	111 07	6644A	0	13 11		
WHITEHALL		03	4HA		45 52	111 59	4277G	0	05 21		
WOLF POINT	INTNL	02	OLF		48 06	105 35	1985A	0	07 11		
NEBRASKA											
AINSWORTH	MUNICIPAL	03	ANW		42 35	099 59	2580A	0	13 11		
ALLIANCE	MUNICIPAL	02	AIA		42 03	102 48	3930A	0	19 11		
BEATRICE	MUNICIPAL	03	BIE		40 19	096 45	1318A	0	13 11 1		
BROKEN BOW	MUNICIPAL	03	BBW		41 26	099 39	2530A	0	13 11		
BURWELL		08	K2C	72555	41 47	099 09	2180	41	04 21 0		
CHADRON	MUNICIPAL	04	CDR		42 50	103 05	3316	0	24 11 8		
COLUMBUS	MUNICIPAL	02	OLU		41 26	097 21	1447A	0	13 11		
GRAND ISLAND	MUNICIPAL	10	GRI	72552	40 58	098 19	1856	41	24 11 4		
HASTINGS	MUNICIPAL	02	HSI		40 36	098 26	1944A	0	15 11		
IMPERIAL	MUNICIPAL	04	IML		40 31	101 37	3284	0	24 11		
KEARNEY	MUNICIPAL	02	EAR		40 44	099 00	2130A	0	15 11		
LINCOLN SC		90			40 49	096 42	1189	0			
LINCOLN	MUNICIPAL	10	LNK	72551	40 51	096 45	1189	0	24 11 4		
MCCOOK	MUNICIPAL	02	MCK		40 13	100 35	2570A	0	14 11		
MULLEN		03	MHN		42 03	101 03	3260A	0	12 11		

ELEVENTH EDITION

W E A T H E R   S E R V I C E   O F F I C E S   A N D   S T A T I O N S

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FC A	PWL	RRT
NEBRASKA											
		10	OFK	72556	41 59	097 26	1551	31	16 11 3		X14
										222	X12

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FC	A	PWL	RRT
NEBRASKA													
NORFOLK	KARL STEFAN MEM	10	OFK	72556	41 59	097 26	1551	31	16	11	3		X14
NORTH PLATTE	LEE BIRD FIELD	14	LBF	72562	41 08	100 41	2787	41	24	11	4	222	X12
OMAHA	EPPLEY AIRFIELD	10	OMA		41 19	095 54	0982	0	24	11	4		
OMAHA N OMAHA	NORTH OMAHA	70	3NC	72553	41 22	096 01	1331	41				222	X14
ONEILL		02	ONL		42 28	98 41		0	25				
SCOTTSBLUFF	MUNICIPAL	10	BFF	72566	41 52	103 36	3958	0	24	11	8		X33
SIDNEY	MUNICIPAL	04	SNY		41 06	102 59	4306	0	24	11	8		
VALENTINE	MILLER FIELD	17	VTN	72567	42 52	100 33	2598	41	15	22	0		
NEVADA													
AUSTIN		07	AUI	72487	39 30	117 05	6608	41					
BATTLE MOUNTAIN	AIRPORT	03	BAM		40 37	116 52	4532A	0	13	11	4		
ELKO	MUNCIPAL	04	EKC		40 50	115 47	5077	0	24	11	8		
ELKO		10			40 50	115 46	5060G	0					
ELY	YELLAND FIELD	10	ELY	72486	39 17	114 51	6262	41	24	11	4	222	
LAS VEGAS	MCCARRAN INTNL	10	LAS	72386	36 05	115 10	2180	41	24	11	4	1	
LOVELOCK	DERBY	04	LOL		40 04	118 33	3904	0	24	11	8		
OWYHEE		08	OWY	72587	41 57	116 06	5401	71	07	21			
RENO SC		80						0					
RENO	MUNICIPAL	14	RNO	72488	39 30	119 47	4400	41	24	11	4	2	
TONOPAH	MUNICIPAL	04	TPH	72485	38 04	117 05	5434	25	24	11	8		
WINNEMUCCA	MUNICIPAL	10	WMC	72583	40 54	117 48	4314	41	24	11	4	222	
YUCCA FLAT		70	UCC	72385	36 57	116 03	3926	0	24	11	8	22	
NEW HAMPSHIRE													
BERLIN	MUNICIPAL	02	BML		44 35	071 11	1158A	0	25				
CONCORD	MUNICIPAL	10	CON	72605	43 12	071 30	0346	31	24	11	5		
JAFFREY		07	AFE	72616	42 43	72 00	1050	21					
KEENE	DILLANT-HOPKINS	02	EEN		42 54	072 16	0482A	0	16	91			
LACONIA	MUNICIPAL	02	LCI		43 34	071 26	0552A	0	12	11			
LEBANON	REGIONAL	04	LEB		43 38	072 19	0570	0	24	11	8		
MANCHESTER	GRENIER FD/MHT M	05	MHT		42 56	071 26	0233A	0	24	11			
MT WASHINGTON		08	MWN	72613	44 16	071 18	6267	81	08	41	0		
WOLFEBORO		07		72615	43 36	071 14	0720	21					

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RPT
NEW JERSEY											
ATLANTIC CITY	NAFEC POMONA	10	ACY	72407	39 27	074 34	0067	41	24 11 4		5E1
BARNEGAT LS		09		74590	39 46	073 46	0020	42			
CAPE MAY	COUNTY	02	WWD		39 01	074 57	00229	0	05 11		
DELAWARE LS		09			38 27	074 35		42			
FIVE FATHOM LS		09		74596	38 47	074 35		42			
MILLVILLE	MUNICIPAL	04	MIV		39 22	075 04	0076	0	24 11 8		
MORRISTOWN	MUNICIPAL	05	MMU		40 49	074 25	0187A	0	17 11		
NEWARK	AIRPORT	10	EWR	72502	40 42	074 10	0030	0	24 11 8		
NEW BRUNSWICK AG		10						0			
TETERBORO	AIRPORT	03	TEB		40 51	074 03	0007A	0	24 11		
TRENTON	MERCER CO	05	TTN		40 17	074 49	0213A	0	24 11		
TRENTON		10	TTNC		40 13	074 46	0190	0			
NEW MEXICO											
ALAMOGORDO	MUNICIPAL	02	ALM		32 50	106 00	4197A	0	19 11		
ALBUQUERQUE	ABQ SUNPT-KIRTLD	40	ABQ	72365	35 03	106 37	5314	41	24 11 4	222	
CARLSBAD	CAVERN CITY AIR T	04	CNM		32 20	104 16	3261	0	24 11 8		
CLAYTON	MUNICIPAL	10	CAO		36 27	103 09	4972	0	03 21 3		
CLOVIS	MUNICIPAL	02	CVN		34 25	103 05	4214A	0	15 11		
CORONA	LINCOLN COMPRESS	03	4CR		34 06	105 41	6500G	0	25 1		
CUBA		03	4SL		36 01	106 57	6902G	0	25 1		
DEMING	MUNICIPAL	04	DMN		32 15	107 42	4324	0	24 11 8		
FARMINGTON	MUNICIPAL	06	FMN		36 45	108 14	5502	0	24 11 4		
GALLUP	SEN CLARKE FLD	02	GUP		35 31	108 47	6467A	0	15 11 1		
GRANTS	GNT-MILAN MUN	04	GNT		35 10	107 54	6524	0	16 11		
HOBBS	LEA CO	06	HOB		32 41	103 12	3666	0	24 11 2		
LAS CRUCES		03	LRU		32 16	106 44	3881G	0	01 1		
LAS CRUCES		30			32 17	106 45	3881G	0			
LAS VEGAS	MUNICIPAL	04	LVS		35 39	105 09	6875	0	24 11 8		
MORIARTY		03	4MY		34 53	106 03	6220G	0	01 11		
RATON	CREWS	01	RTN	72376	36 45	104 30	6376	0			
ROSWELL	MUNICIPAL	14	RNM	72268	33 24	104 32	3619	21	07 11 5	1	
ROSWELL	INDUSTRIAL AIR CTR	05	ROW		33 18	104 31	3666A	0	17 11		
SANTA FE	MUNICIPAL	06	SAF		35 37	106 05	6308	0	24 11 8		
SILVER CITY	SVC-GRANT COUNTY	02	SVC		32 34	108 10	5443A	0	14 11		
SOCORRO		03	ONM		34 03	106 53	4625	0	02 21 6		
TRUTH OR CONS	MUNICIPAL	04	TCS		33 14	107 16	4858	0	24 11 4		
TUCUMCARI	MUNICIPAL	04	TCC		35 11	103 36	4039	0	24 11 8		
ZUNI	INTERMEDIATE FIELD	04	ZUN		35 06	108 44	6447	0	24 11 8		

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWUL	RPT
NEW YORK													
ALBANY	COUNTY	10	ALB	72518	42 45	073 48	0292	41	24	11	4	222	X34
AMBROSE LT		09		74499	40 27	073 49	94	82					
AMITYVILLE	ZAHNS	02	AYZ		40 42	073 24	0054A	0	12	11			
BETHPAGE	GRUMMAN	02	BPA		40 44	073 29	0119A	0	12	12			
BINGHAMTON	BROOME CO	10	BGM	72515	42 13	075 59	1638	41	24	11	4	2	X34
BUFFALO	GRTR BUFFALO INT	10	BUF	72528	42 56	078 44	0706	41	24	11	4	222	561
BUFFALO		09		74/52	42 53	078 53		44					
CALVERTON	PECONIC RIVER	02	CTC		40 55	072 47	0075A	0	13	12			
DANSVILLE	MUNICIPAL	07	DSV	72523	42 34	77 43	686	31					
ELMIRA	CHEMUNG CO	04	ELM		42 10	076 54	0954	0	24	11	8		
FARM. DALE	REPUBLIC	05	FRG		40 44	073 26	0082A	0	17	11			
FORT NIAGARA		09		62/	43 16	079 04		44					
GLENS FALLS	WARREN CO	04	GFL		43 21	073 37	0333	0	24	11	8		
ISLIP	LONG IS/MACARTHUR	04	ISP		40 47	073 06	0108	0	24	11	8		
ITHACA	TOMPKINS CO	02	ITH		42 29	076 28	1098	0	20	11			
ITHACA SC		40						0					
JAMESTOWN	MUNICIPAL	02	JHW		42 09	079 15	1723A	0	18	11			
MASSENA	RICHARDS MUN	04	MSS		44 56	074 51	0208	0	24	11	8		
MONTICELLO	SULLIVAN CTY INTL	02	MSV		41 42	74 44	1413	0	09	11			
NEWBURGH	STEWART	02	SWF					0					
NEW YORK		40	NYC				0087	0					
NEW YORK		10			40 46	73 59	87	0					561
NEW YORK RH								0					
NEW YORK	KENNEDY INTNL	10	JFK	74486	40 39	073 47	0022	41	24	11	0	22	
NEW YORK	LAGUARDIA FIELD	10	LGA	72503	40 46	073 54	31	41	24	11	4		2
NEW YORK AWP								0					
OGDENSBURG	MUNICIPAL	02	OGS		44 41	075 28	0300	0	07	22			
OLEAN	MUNICIPAL	02	OLE		42 14	078 22	2120A	0	05	11			
ONEONTA	MUNICIPAL	07		745/1	42 31	75 04	1775	41					
PLATTSBURG	CLINTON CO	02	PLB		44 41	073 31	0371A	0	19	11			
POUGHKEEPSIE	DUTCHESS CO	04	POU		41 38	073 53	0162	0	24	11	8		
ROCHESTER	ROC-MONROE CO	10	ROC	72529	43 07	077 40	0555	41	24	11	4		
ROCHESTER	HARBOR	09		726/2	43 15	077 37		44					
SARANAC LAKE	ADIRONDACK	02	SLK		44 23	74 12	1659A	0	12	11			
SCHENECTADY	COUNTY	07	SCH		42 51	073 57	0378A	0	15	11			
SYRACUSE	HANCOCK	10	SYR	72519	43 07	076 07	0408	41	24	11	4	2	
UTICA	ONEIDA CO	04	UCA		43 09	075 23	0744	0	24	11	8		
WATERTOWN	MUNICIPAL	04	ART		44 00	076 01	0333	0	24	11	8		
WHITE PLAINS	WESTCHESTER CO	03	HPN		41 04	073 43	0443	0	24	11			

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RRT
NORTH CAROLINA											
ASHEVILLE NCC											
ASHEVILLE	MUNICIPAL	10	AVL	72315	35 26	082 32	2170	41	24 11 4		
CAPE HATTERAS		10	HAT	72304	35 16	075 33	0011	41	24 11 4	222	651
CHARLOTTE	DOUGLAS MUN	10	CLT	72314	35 13	080 56	0769	41	24 11 4		
DIAMOND SHOALS	LGT STN	09		74696	35 09	075 18		42			
ELIZABETH CITY	CG AIR STN	04	ECG	74694	36 16	076 11	0013	0	15 11 6		
FAYETTEVILLE	MUN GRANNIS FD	06	FAY		35 00	078 53	0196	0	24 11		
FRYING PAN SHOALS		09		74699	33 29	077 35		42			
GREENSBORO	GSO HIGH POINT	10	GSO	72317	36 05	079 57	0886	41	24 11 4	222	
HICKORY	MUNICIPAL	04	HKY		35 45	081 23	1188	0	24 11 8		
HOT SPRINGS		03	HSS		35 54	082 49	1486G	0	07 11		
KINSTON	STALLINGS	02	ISO		35 19	077 38	0093A	0	18 11		
NEW BERN	SIMMONS-NOTT	04	EWN		35 05	77 03	0024	0	24 11 8		
RALEIGH	RALEIGH DURHAM	40	RDU	72306	35 52	078 47	0441	41	24 11 4	2	K33
RALEIGH SC		40						0			
ROCKY MOUNT	MUNICIPAL	04	RMT		35 54	077 48	0122	0	24 11 8		
ROCKY MOUNT WILSON	AIRPORT	02	RWI		35 51	77 53	158A	0	15 11		
SOUTHERN PINES	PINEHURST-SOPINES	02	SOP		35 14	079 24	0470	0	15 11		
WILMINGTON	NEW HANOVER CO	10	ILM		34 16	077 55	0038	0	24 11 8		571
WINSTON SALEM	SMITH REYNOLDS	32	INT		36 04	080 14	0978	0	24 11		
NORTH DAKOTA											
BISMARCK	MUNICIPAL	10	BIS	72764	46 46	100 45	1660	41	24 11 4	222	
DEVILS LAKE		07		72757	48 07	098 52	1478	41			
DEVILS LAKE	MUNICIPAL	32	DVL		48 07	098 54	1450A	0	13 11		
DICKINSON	MUNICIPAL	04	DIK		46 47	102 48	2583	0	24 11 8		
FARGO	HECTOR	10	FAR	72753	46 54	096 49	0899	41	24 11 4	2	
FARGO SC		40						0			
GRAND FORKS	INTNL	04	GFK		47 57	097 11	0832	0	24 11 8		
JAMESTOWN	MUNICIPAL	04	JMS		46 55	098 41	1494	0	24 11 8		
MINOT	INTERNATIONAL	04	MOT		48 16	101 17	1714	0	24 11 8		
WILLISTON	SLOULIN FI INTNL	10	ISN	72767	48 11	103 38	1905	41	24 11 4	2	
OHIO											
AKRON	AKRON CANTON	10	CAK	72521	40 55	081 26	1236	41	24 11 4		K03
AKRON	MUNICIPAL	06	AKR		41 02	081 28	1052	0	24 11		
ASHTABULA LS		09		74527	41 55	080 48	0586	44			
ATHENS	OHIO UNIV	02	LOA		39 21	082 04	0632A	0	04 21		
CINCINNATI	GR CINCINNATI	10	CVG	72421	39 04	084 40	0877	41	24 11 4	2	561
CINCINNATI		10			39 06	084 31	0627	0			

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RRT
OHIO											

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWU	RRT
OHIO													
CINCINNATI RFC		60						0					
CINCINNATI	MUN LUNKEN FD	04	LUK		39 06	084 26	0497	0	24	11	4		
CINCINNATI	ABBE OBSERVATORY	70			39 08	084 31	0627	0					
CLEVELAND	HOPKINS INTNL	40	CLE	72524	41 24	081 51	0805	41	24	11	4		X33
CLEVELAND	BURKE LAKEFRONT	05	BKL		41 31	081 41	0584A	0	17	11			
CLEVELAND	CUYAHOGA CO	02	CGF		41 34	081 29	0874A	0	03	21			
CLEVELAND LS		09	LIX		41 33	081 47	0597	44					
COLUMBUS	PORT COLUMBUS	10	CMH	72428	40 00	082 53	0837	41	24	11	4	1	X33
COLUMBUS	OHIO STATE U	05	OSU		40 05	083 04	0904	0	17	11			
COLUMBUS		40			39 59	083 00	0724G	0					
DAYTON		70			39 52	084 07	0979	0				22	
DAYTON	J M COX DAY MUN	10	DAY	72429	39 54	084 13	1003	41	24	11	4		
FINDLAY	AIRPORT	04	FDY		41 01	083 40	0803	0	24	11	8		
LIMA	ALLEN CO	02	AOH		40 42	084 02	975A	0	10	11			
MANSFIELD	LAHM MUNICIPAL	15	MFD		40 49	082 31	1312	0	24	11	4		
MARBLEHEAD LS		09	PNF		41 33	082 44	0644	44					
PORTSMOUTH	SCIOTO CO	02	PMH		38 50	082 51	0664A	0	10	11			
TOLEDO		09		74753	41 42	83 27		0					
TOLEDO	TOL EXPRESS	10	TOL	72536	41 36	083 48	0692	41	24	11	4	2	
YOUNGSTOWN	MUNICIPAL	10	YNG	72525	41 16	080 40	1186	41	24	11	4		
ZANESVILLE	MUNICIPAL	04	ZZV		39 57	81 54	902	0	24	11	8		
OKLAHOMA													
ALTUS	MUNICIPAL	02			34 42	99 20	1426A	0	25				
ARDMORE	MUNICIPAL	05	ADM		34 18	097 01	0772	C	24	11			
BARTLESVILLE	PHILLIPS	02	BVO		36 45	096 00	0713A	0	16	11			
CLINTON	CLINTON SHERMAN	05	CSM					0	13	12			
DUNCAN	HALLIBURTON-MUN	02	DUC		34 29	097 58	1125A	0	15	11			
ENID	WOODRING FIELD	02	WDG		36 23	097 49	1163A	0	14	11			
GAGE	INTERMEDIATE FLD	04	GAG		36 18	099 46	2202	0	24	11	8		
HOBART	MUNICIPAL	04	HBR		35 00	099 03	1570	C	24	11	8		
LAWTON	MUNICIPAL	02	LAW		34 34	098 25	1108A	0	19	11			
MCALESTER	MUNICIPAL	04	MLC		34 53	095 47	0744	0	24	11	8		
MUSKOGEE	DAVIS	02	MKO		35 40	095 22	0610A	0	09	11			
NORMAN NSSL								C					
OKLAHOMA CITY SC		80			35 29	97 31	1213G	0					
OKLAHOMA CITY	WILL ROGERS WORLD	40	OKC	72353	35 24	097 36	1304	41	24	11	4		561
OKLAHOMA CITY	WILEY POST	04	PWA		35 32	097 38	1299A	0	24	11			
PONCA CITY	MUNICIPAL	04	PNC		36 44	097 06	0998	0	24	11	8		
POTEAU	ROBT S KERR	02			35 01	94 37	451A	0	25				
STILLWATER	SEARCY	02	SWO		36 10	097 05	0985A	0	03	11			

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RRT
OKLAHOMA											
TULSA	RIVERSIDE	05	RVS		36 02	095 59	625A	0	16 11		
TULSA	INTNL	10	TUL	72356	36 12	095 54	0676	41	24 11 4	2	X33
TULSA RFC		60			36 09	96 00	7030	0			
WOODWARD	WEST WOODWARD	02			36 26	99 31	2187	0	25		
OREGON											
ASTORIA	CLATSOP CO	10	AST	72791	46 09	123 53	0022	41	24 11 4		
BAKER	MUNICIPAL	04	BKE		44 50	117 49	3373	0	24 11 8		
BROOKINGS		07	4BK	72598	42 03	124 17	0085	71	07 21		
BURNS		10	4BW	72683	43 35	119 03	4170	81	08 41 0	4	
CAPE BLANCO LS		09		72599	42 50	124 34	0188	61			
CASCADE LOCKS	AIRPORT	03	CZK		45 41	121 53	0158G	0	06 31		
COLUMBIA RIVER LS		09	NCR		46 11	124 11	0018	81			
CORVALLIS	MUNICIPAL	02	CVO		44 30	123 17	0246A	0	15 11		
CORVALLIS AG		10						0			
EUGENE	MAHLON SWEET FLD	10	EUG	72693	44 07	123 13	0377	81	24 11 4	2	
HILLSBORO	PORTLAND-HLSBORO	05	HIO		45 32	122 57	0204A	0	17 11		
KLAMATH FALLS	KINGSLEY MUN FD	10	LMT		42 09	121 44	4102	0			
LAKEVIEW		07	4LW	72589	42 11	120 21	4764	81	08 41 0		
MEACHAM	EMERGENCY	71	MEH		45 33	118 24	4056	0	24 11 2		
MEDFORD	MFR-JACKSON CTY	10	MFR	72597	42 22	122 52	1329	41	24 11 4	22	
NEWPORT		07	ONW	72695	44 38	124 03	0159	81	08 41 0		
NEWPORT		10						0			
NORTH BEND	MUNICIPAL	04	OTH		43 25	124 15	0017	0	24 11 8		
ONTARIO	AIRPORT	02	ONO		44 01	117 01	2189	0	09 12		
PENDLETON	PENDLETON FIELD	10	PDT	72688	45 41	118 51	1495	41	24 11 4	2	
PORTLAND	INTNL	40	PDX	72698	45 36	122 36	0039	41	24 11 4		
PORTLAND FW								0			
PORTLAND RFC		60			45 32	122 40		0			
PORTLAND SC		40			45 32	122 41	0032G	0			
REDMOND	ROBERTS	04	RDM		44 16	121 09	3084	0	24 11 9		
ROSEBURG	MUNICIPAL	03	RBG		43 14	123 22	525A	0	11 11		
SALEM	MCNARY FIELD	10	SLE	72694	44 55	123 01	0201	41	24 11 4	122	
SALEM FW					44 55	123		0			
SEXTON SUMMIT		71	SXT		42 37	123 22	3841	0	24 11 3		
THE DALLES	MUNICIPAL	04	DLS		45 37	121 09	0219	0	24 11 9		
TROUTDALE	AIRPORT	31	TTD		45 33	122 24	37	0	24 11		

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PMUL	RRT
PENNSYLVANIA													
ALLENTOWN	A BETHLEHEM EASTN	10	ABE	72517	40 39	075 26	0385	41	24	11	4		
ALTOONA	BLAIR CO	04	AOO		40 18	078 19	1469	0	24	11	8		
BLAIRSVILLE		03	BSI		40 27	079 09	2147G	0	16	11	4		
BRADFORD	REGIONAL	04	BFD		41 48	078 38	2150	0	24	11	8		
DUBOIS	JEFFERSON CO	04	DUJ		41 11	078 54	1824	0	24	11	7		
ERIE	INTNL	10	ERI	72526	42 05	080 11	0737	0	24	11	8		
ERIE HARBOR LBS		09		74572	42 07	080 05	0578G	44					
FRANKLIN	CHESS LAMBERTON	02	FKL		41 23	079 52	1540A	0	13	11			
HARRISBURG	HARRISBURG STATE	10	HAR	72511	40 13	076 51	0351	41	24	11	4	2	
HARRISBURG		10			40 16	76 53		0					
HAZLETON	MUNICIPAL	02	HZL		40 59	076 00	16044	0	15	11			
INDIANA	IND CO J STEWART FD	02	5G5					0	02	22			
JOHNSTOWN	JST-CAMBIA CO	04	JST		40 19	078 50	2284A	0	16	11			
LANCASTER	MUNICIPAL	05	LNS		40 04	076 19	0407A	0	16	11			
LATROBE	WESTMORELAND LTRBE	02	LBE					0	16	11			
MIDDLETOWN	OLMSTED STATE	05	MDT		40 12	076 46	318A	0	17	11			
PHILADELPHIA	INTNL	40	PHL	72408	39 53	075 15	0028	41	24	11	4	2	
PHILADELPHIA		70			39 55	75 11	16	0					2
PHILADELPHIA	N PHILADELPHIA	03	PNE		40 05	075 01	0119	0	24	11			
PHILIPSBURG	MID-STATE	04	PSB		40 53	078 05	1914	0	24	11	8		
PITTSBURGH	GREATER PIT	10	PIT	72520	40 30	080 13	1225	41	24	11	4		
PITTSBURGH	ALLEGHENY CO	04	AGC		40 21	079 56	1273	0	24	11			
PITTSBURGH WSFO		40			40 27	080 00	1017	0					
PITTSBURGH	MOON TOWNSHIP	70		72520	40 32	080 14	1183	0				222	451
READING	GEN SPAATZ FD MUN	05	RDG		40 23	075 58	353	0	24	11			
TOBYHANNA		03	ZTP		41 11	075 25	19205	0	08	41			
UNIVERSITY PARK SF		90						0					
WILKESBARRE SCRANTON	WILKES BARRE	10	AVP	72513	41 20	075 44	0968	41	24	11	4		
WILLIAMSPORT	IPT-LYCOMING CO	14	IPT	72514	41 15	076 55	0525	0	24	11	8	1	
RHODE ISLAND													
BLOCK ISLAND	BID STATE	11	BID		41 10	071 35	0118	0	24	12	3		
PROVIDENCE	T F GREEN STATE	10	PVD	72507	41 44	071 26	0062	41	24	11	4		
WESTERLY	STATE	02	WST		41 21	071 48	0081A	0	10	11			
SOUTH CAROLINA													
AIKEN	MUNICIPAL	02	AIK		33 39	81 41	530	0	03	22			
ANDERSON	COUNTY	04	AND		34 30	082 43	0773	0	24	11	6		
CHARLESTON		17		72208	32 47	079 56	12	22					
CHARLESTON	MUNICIPAL	10	CHS	72208	32 54	080 02	0048	41	24	11	8	222	561

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RRT
SOUTH CAROLINA											
CLEMSON AG		10			34 41	82 49	0196	0			
COLUMBIA	METROPOLITAN	4[illegible]	CAE	72310	33 57	081 07	0226	41	24 11 4		XXX
FLORENCE	MUN GILBERT FLD	34	FLO		34 11	079 43	0151	0	24 11 4		
GREENVILLE	MUNICIPAL DT	16	GRL		34 51	082 21	1154	0	17 11		
GREENVILLE-SPRTNBG	GRNV-SPA JET AGE	10	GSP	72312	34 54	082 13	0971	41	24 11 4		
GREENWOOD	COUNTY	02	GRD		34 15	082 09	0631A	0	14 11		
MYRTLE BEACH NORTH	MUNICIPAL	12	CRE		33 49	078 43	0037A	0	14 11		
SPARTANBURG	DT MEMORIAL	3[illegible]	SPA		34 55	081 57	0826	0	16 11		
SOUTH DAKOTA											
ABERDEEN	MUNICIPAL	10	ABR	72659	45 27	098 26	1300	41	24 11 4		
BROOKINGS SC		90						0			
BROOKINGS	MUNICIPAL	02	BKX		44 19	096 48	1637A	0	14 11		
HURON	W W HOWES MUN	14	HON	72654	44 23	098 13	1286	31	24 11 5	1	
HURON MOBILE UAV		76						0		22	
LEMMON		14	LEM	72669	45 56	102 10	2602	41	04 51 0		
MITCHELL	MUNICIPAL	12	MHE		43 46	098 02	1302A	0	16 11		
MOBRIDGE		17	MBG	72668	45 32	100 26	1664	41	04 41		
PHILIP	AIRPORT	13	PHP		44 03	101 36	2212	0	16 21 4		
PICKSTOWN		17		72652	43 04	098 32	1485	41			
PIERRE	MUNICIPAL	34	PIR		44 23	100 17	1726	0	24 11 8		
RAPID CITY	REGIONAL		RAP	72662	44 03	103 04	3164	41	24 11 4	222	
SIOUX FALLS	FOSS FIELD	1[illegible]	FSD	72651	43 34	096 44	1427	41	24 11 4		X12
WATERTOWN	MUNICIPAL	14	ATY		44 55	097 09	1740	0	24 11 4		
YANKTON	GURNEY MUN	02	YKN		42 55	097 23	1307A	0	17 11		
TENNESSEE											
BRISTOL	TRI-CITY	10	TRI	72314	36 29	082 24	1526	0	24 11 8		
CHATTANOOGA	LOVELL	10	CHA	72324	35 02	085 12	0688	41	24 11 4		
CLARKSVILLE	OUTLAW FIELD	[illegible]2	CKV		36 37	087 25	0540A	0	14 11		
CROSSVILLE	MEMORIAL	34	CSV		35 57	085 05	1470	0	24 11 8		
DYERSBURG	MUNICIPAL	14	DYR		36 01	089 24	0345	0	17 11 6		
JACKSON	MCKELLAR	14	MKL		35 36	088 55	0422	0	24 11 4		
JACKSON AG		1[illegible]			35 37	088 5[illegible]		0			
KNOXVILLE	MUNICIPAL	10	TYS	72326	35 49	083 59	0983	41	24 11 4	[illegible]	
MEMPHIS	INTNL	40	MEM	72334	35 03	089 59	0284	41	24 11 4	[illegible]	
MEMPHIS		70						0			XX1
MONTEAGLE		03	MGL		35 15	85 51		0	06 21		
NASHVILLE	METROPOLITAN	10	BNA	72327	36 07	086 41	0605	41	24 11 4		

ELEVENTH EDITION

STATION NAME AIRPORT NAME TYPE CALL NO. LAT. LONG. ELEV. SC AV FD A PWU RRT

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FO A	PWU	RRT
TENNESSEE											
NASHVILLE	OLD HICKORY	70		72327	36 15	086 34	0591	C		22	651
SHELBYVILLE	BOMAR	02	SYI		35 33	086 26	0802A	0	08 11		
TEXAS											
ABILENE	MUNICIPAL	10	ABI	72266	32 26	099 41	1753	41	24 11 4	4	X11
ABILENE MOBILE UAU		70	ABI		32 26	099 41	1753	0		22	
ALICE	INTERNATIONAL	04	ALI		27 44	098 02	0180	0	24 11 8		
ALPINE		07		72262	30 21	103 40	4436	71			
AMARILLO	MUNICIPAL	10	AMA	72363	35 14	101 42	3604	41	24 11 4	22	561
AUSTIN	MUELLER MUN	10	AUS	72254	30 19	097 42	0621	41	24 11 4		X33
BIG SPRING	HOWARD CO	02	HCA		32 19	101 27	2564A	0	15 11		
BROWNSVILLE	RIO GRAND INT VLY	10	BRC	72250	25 54	097 26	0020	41	24 11 4	222	561
BROWNWOOD	MUNICIPAL	02	BWD		31 49	098 57	1386	0	14 11		
CHILDRESS	MUNICIPAL	04	CDS		34 26	100 17	1952	0	24 11 4		
COLLEGE STATION	EASTERWOOD	04	CLL		30 35	96 22	0328	0	24 11 8		
CORPUS CHRISTI	INTNL	10	CRP	72251	27 46	097 30	0044	41	24 11 4		X33
COTULLA	MUNICIPAL	04	COT		28 27	099 13	0479	0	24 11 8		
DALHART	MUNICIPAL	04	DHT		36 01	102 33	3997	0	24 11 8		
DALLAS	LOVE FIELD	10	DAL	72258	32 51	096 51	0488	41	24 11 4		
DALLAS	ADDISON	05	ADS		32 59	096 50	0643A	0	16 11		
DALLAS	REDBIRD	05	RBD		32 41	096 52	0660A	0	16 11		
DEL RIO	INTNL	10	DRT	72261	29 22	100 55	1027	41	24 11 4	22	
EL PASO	INTNL	10	ELP	72270	31 48	106 24	3916	41	24 11 4	222	
FT WORTH	MEACHAM	04	FTW		32 49	097 21	0706	0	24 11		
FT WORTH	GTR SW INTNL	70	GSW	72259	32 50	097 03	0576	41	24 11 4		561
FT WORTH RH								0			
FT WORTH UAU	CARSWELL AFB	70		72259	32 46	097 25		0		22	
FORT WORTH WSFO		40			32 45	97 15	616G	0			
GALVESTON	SCHOLES FIELD	31	GLS		29 16	094 52	0009	0	24 11		
GALVESTON		10	GLS	72242	29 18	094 49	0054	41			561
GREENVILLE	MAJORS	02	GVT		33 04	096 04	0540A	0	25		
GUADALUPE PASS		01	GDP		31 50	104 48	5460	0	24 11		
HARLINGEN	MUNICIPAL	02	HRL		26 13	097 40	0035A	0	17 11		
HONDO		70						0			
HOUSTON	WM P HOBBY	04	HOU		29 39	095 17	0062	0	24 11		
HOUSTON	INTERCONTINENTAL	10	IAH	72243	29 59	95 22	108	41	24 11 4		
HOUSTON		10	HCUC		29 46	095 22	0041G	C			
JUNCTION	KIMBLE CO	03	JCT		30 30	099 46	1713	C	03 21 3		
LAKE JACKSON	BRAZORIA COUNTY DOW	02	LJN					0	25		
LAREDO	MUNICIPAL	02	LOT		27 36	99 31	527A	0	19 11		
LONGVIEW	GREGG CO	06	GGG		32 23	094 43	0373	C	24 11 4		

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STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWU	RPT
TEXAS											
LUBBOCK	WEST TEXAS AIR TERM	10	LBB	72267	33 39	101 49	3241	41	24 11 4		X13
LUBBOCK ASO		10			33 39	101 51	3245G	0			
LUFKIN	ANGELINA CO	04	LFK		31 14	094 45	0316	0	24 11 8		
MARFA	MUNICIPAL	03	MRF		30 22	104 01	4858	0	06 21 5		
MCALLEN	MILLER INTNL	04	MFE		26 11	098 14	0112	0	24 11 4		
MIDLAND	MAF ODESSA REG AT	10	MAF	72265	31 56	102 12	2862	41	24 11 4	222	X11
MINERAL WELLS	MUNICIPAL	04	MWL		32 47	098 04	0972	0	24 11 4		
PALACIOS	MUNICIPAL	04	PSX		28 43	096 15	0015	0	24 11 8		
PARIS	COX	02	PRX		33 38	095 27	0547A	0	10 11		
PLAINVIEW	HALE CO	05	PVW		34 10	101 43	3372A	0	17 11		
PORT ARTHUR	JEFFERSON CO	15	BPT	72241	29 57	094 01	0022	0	24 11 6		
SAN ANGELO	MATHIS	10	SJT	72263	31 22	100 30	1908	41	24 11 4		X13
SAN ANTONIO	STINSON FLD MUN	05	SSF		29 20	098 28	0577A	0	17 11		
SAN ANTONIO	INTNL	40	SAT	72253	29 32	098 28	0794	41	24 11 4		X13
TEMPLE	DRAUGHON MILLER	02	TPL		31 09	097 25	682A	0	19 11		
TYLER	POUNDS FIELD	06	TYR		32 22	095 24	0551	0	24 11 4		
UVALDE	GARNER FIELD	02	UVA		29 13	99 45	941G	0	25		
VICTORIA	FOSTER	10	VCT	72255	28 51	096 55	0117	41	24 11 4	222	XS3
WACO	MUNICIPAL	10	ACT	72256	31 37	097 13	0508	41	24 11 4	3	X13
WESLACO AG		10			26 03	097 58	0077	C			
WICHITA FALLS	MUNICIPAL AIR TERM	10	SPS	72351	33 58	098 29	1030	41	24 11 4		X13
WINK	WINKLER CO	04	INK		31 47	103 12	2820	0	24 11 8		
UTAH											
BLANDING		08	4BL	72472	37 37	109 28	6039	41	08 21		
BRYCE CANYON	AIRPORT	04	BCE		37 42	112 09	7586	0	24 11 4		
BULLFROG MARINA		03	U17		37 33	110 43	3606G	C	04 21		
CEDAR CITY	MUNICIPAL	04	CDC		37 42	113 06	5618	0	24 11 8		
DELTA	MUNICIPAL	04	DTA		39 23	112 31	4761	C	13 11		
DELTA		03	4SW		39 21	112 34	4761	0	09 41 4		
GREEN RIVER		07	U20	72477	39 03	110 09	4087	41			
HANKSVILLE		03	4HV		38 22	110 43	4312	C	15 21 8		
LOGAN		40						0			
MILFORD	MUNICIPAL	10	MLF	72475	38 26	113 01	5033	0	11 11 4	1	
MOAB	CANYONLAND	02	CNY		38 46	109 45	4574A	0	15 11		
OGDEN	MUNICIPAL	05	OGD		41 11	112 01	4455E	0	17 11		
PRICE	CARBON CO	01	PUC		39 37	110 45	5901	0	24 11		
ROOSEVELT		07		72470	40 18	109 59	5106	41			
SALT LAKE CITY	INTNL	40	SLC	72572	40 46	111 58	4227	41	24 11 4	22	
SALT LAKE CITY 2F								0			
SALT LAKE CITY REC		60			40 46	111 51		0			

STATION NAME AIRPORT NAME TYPE CALL NO. LAT. LONG. ELEV. SC AV FD A PWUL RPT

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PHUL RRT
UTAH										
VERNAL	MUNICIPAL	02	VEL		40 27	109 31	5259	0	10 11	
WENDOVER	AUXILIARY	11	ENV	72581	40 44	114 02	4239	0	24 11 3	1
VERMONT										
BENNINGTON	MUNICIPAL	07	585	72516	42 53	73 15	00823	21		
BURLINGTON	INTNL	10	BTV	72617	44 28	073 09	0340	41	24 11 4	1
MONTPELIER	BARRE	04	MPV		44 12	072 34	1121	0	24 11 8	
NEWPORT	STATE	02	EFK		[illegible]	[illegible]	[illegible]		[illegible]	
NEWPORT		07		72612	44 56	072 12	0766	41		
RUTLAND	STATE	02	RUT		43 32	072 57	787A	0	16 11	
ST JOHNSBURY		07		72614	44 25	072 01	0711	21		
SPRINGFIELD	STATE	[illegible]	VSF		[illegible]	[illegible]	57?A		[illegible]	
VIRGINIA										
BLACKSBURG SC		80						0		
BLACKSTONE	AFB	04	BKT		37 05	077 57	0438	0	16 11 5	
CHARLOTTESVILLE	ALBEMARLE	04	CHO		38 08	078 27	0644	0	24 11 8	
CHESAPEAKE LS		09		74599	36 54	075 43		42		
DANVILLE	MUNICIPAL	04	DAN		36 34	079 20	0590	0	24 11 8	
HOT SPRINGS	INGALLS FIELD	02	HSP		37 57	079 49	3801	0	15 11	
LYNCHBURG	MUNICIPAL	15	LYH	72410	37 20	079 12	0937	31	18 11 2	
NEWPORT NEWS	PAT HENRY	04	PHF		37 08	076 30	0051	0	24 11 8	
NORFOLK	ORF REGIONAL	10	ORF	72308	36 54	076 12	0030	41	24 11 4	
NORFOLK AWP								0		
PULASKI	NEW RIVER VALLEY	02	PSK		37 08	080 41	2105A	0	13 11	
RICHMOND	BYRD FIELD	10	RIC	72401	37 30	077 20	177	41	24 11 4	2
ROANOKE	MUNICIPAL	10	ROA	72411	37 19	079 58	1176	41	24 11 4	
STAUNTON	SHENANDOAH VALLEY	02	SHD		38 16	078 51	1192A	0	15 11	
WALLOPS IS UAU		70		72402	37 51	075 29	00096	51	09 11	22
WALLOPS STATION	NASA WBSF	10	WAL		37 56	075 28	004P	0	12 12 4	
WASHINGTON RFC		60						0		
WASHINGTON NMC		20						0		
WASHINGTON DULLES	DULLES INT'L VA	10	IAD	72403	38 57	077 27	0322	41	24 11 4	
WASHINGTON		40						0		
WASHINGTON	NATIONAL	10	DCA	72405	38 51	077 02	0065	41	24 11 4	
WASHINGTON UAU		70			38 59	077 29	0276	0		22

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STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWL	RRT
WASHINGTON													
AUBURN		10	ZSE		47 17	122 11	2916	0					
BELLINGHAM	MUNICIPAL	04	BLI		48 49	122 32	0159	0	24	11	9		
BREMERTON	KITSAP CO	03	PWT		47 29	122 46	0482A	0	10	11			
COLVILLE		07	63S	72787	48 32	117 53	1862	41	04	51			
EPHRATA	MUNICIPAL	04	EPH		47 19	119 31	1259	0	24	11	9		
EVERETT	PAINE FIELD	05	PAE		47 55	122 17	613	0	17	11			
HOQUIAM	BOWERMAN	04	HQM		46 58	123 56	0015	0	24	11	8		
MOSES LAKE	GRANT COUNTY	05	MWH		47 12	119 19	1196	0	17	11			
OLYMPIA	AIRPORT	10	OLM		46 58	122 54	0200	0	24	11	9		
OLYMPIA FW								0					
OMAK		07	40M	72789	48 26	119 32	1232	91	09	41	8		
PASCO	TRI-CITIES	02	PSC		46 16	119 07	406A	0	20	11			
PORT ANGELES	AIR STATION	09	NOW	74201	48 09	123 24	0029	41	24	11	4		
PULLMAN	PUW-MOSCOW	02	PUW		46 45	117 07	2551A	0	19	11			
QUILLAYUTE	AIRPORT	10	UIL	72797	47 57	124 33	0205	41	24	11	4	22	
RENTON	AIRPORT	05	RNT		47 30	122 13	0029A	0	17	11			
SEATTLE	BOEING FLD INTNL KNG	04	BFI		47 32	122 18	0030	0	24	11			
SEATTLE TACOMA	INTNL	10	SEA	72793	47 27	122 18	0450	41	24	11	4		
SEATTLE WSFO		40			47 36	122 20	00146G	0					
SEATTLE PWP								0					
SHELTON		03	SHN		47 15	123 09	02746G	0	06	11			
SPOKANE	INTNL	10	GEG	72785	47 38	117 32	2365	41	24	11	4	222	
SPOKANE	FELTS	04	SFF		47 40	117 20	1968	0	24	11	1		
STAMPEDE PASS		70	SMP		47 17	121 20	3967	0	16	11	6		
TACOMA	INDUSTRIAL	02	TIW		47 16	122 35	292A	0	09	12			
TOLEDO	WINLOCK	04	TDO		46 23	122 49	0379	0	17	11	6		
UMATILLA REEF LS		09	NNCL		48 10	124 51	0010	81					
WALLA WALLA	CITY-COUNTY	04	ALW		46 06	118 17	1207	0	24	11	9		
WALLA WALLA		10			46 02	118 20	0991	0					
WENATCHEE	PANGBORN	04	EAT		47 24	120 12	1255	0	24	11	9		
WENATCHEE		10			47 33	120 20	900	0					
YAKIMA	MUNICIPAL	10	YKM	72791	46 34	120 32	1066	41	24	11	4	2	
WEST VIRGINIA													
BECKLEY	RALEIGH CO MEM	10	BKW	72412	37 47	081 07	2514	41	24	11	4	1	
BLUEFIELD	MERCER CO	04	BLF		37 13	081 13	2867	0	24	11	9		
CHARLESTON	KANAWHA	10	CRW	72414	38 22	081 36	0951	41	24	11	4		
CLARKSBURG	BENEDUM	02	CKB		39 17	080 14	1183	0	17	11			
ELKINS	EKN RANDOLPH CO	10	EKN	72417	38 53	079 51	1997	0	16	11	5		
HUNTINGTON	TRI-STATE	14	HTS	72425	38 22	082 33	0838	31	24	11	5	122	
KEARNEYSVILLE AG		10			39 23	077 53	0550G	0					
MARTINSBURG	MUNICIPAL	04	MRB		39 24	077 59	0534	0	24	11	8		

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWU	RRT
WEST VIRGINIA													
MORGANTOWN	MUNICIPAL	04	MGW		39 39	079 55	1253	0	24	11	8		
MORGANTOWN SC		80						0					
PARKERSBURG		10	PKB		39 16	081 34	0637	0					
PARKERSBURG	PKB-WOOD COUNTY	04	PKB		39 21	081 26	0864	0	24	11	8		
WHEELING	WHLG-OHIO CO	06	HLG		40 11	080 39	1196A	0	24	11			
WHITE SULPHUR SP	GREENBRIER	02	SSL		37 46	080 20	1901A	0	11	11			
WISCONSIN													
APPLETON	OUTAGAMIE CO	02	ATW		44 16	088 31	0918A	0	17	11			
ASHLAND	JFK MEMORIAL	02	ASX		46 33	90 55	826A	0	25				
EAU CLAIRE	MUNICIPAL	04	EAU		44 52	091 29	0895	0	24	11	8		
FOND DU LAC	COUNTY	02	FLD		43 46	88 29	809A	0	25				
GREEN BAY	AUSTIN STRAUBEL	10	GRB	72645	44 29	088 08	0702	41	24	11	4	222	
HAYWARD	AIRPORT	02	HYR		46 01	91 27	1217A	0	25				
JANESVILLE	ROCK COUNTY	32	JVL		42 37	089 02	0808A	0	18	11			
KENOSHA		09			42 35	87 45	730G	42					
LACROSSE	MUNICIPAL	04	LSE		43 52	091 15	663	0	24	11	8		
LACROSSE		10						C					
LAND O LAKES	MUNICIPAL	02	LNL		46 03	89 13	1706A	0	25				
LONE ROCK	TRI COUNTY	04	LNR		43 12	090 11	0721	0	24	11	8		
MADISON	TRUAX FIELD	10	MSN	72641	43 08	089 20	0866	41	24	11	4	2	×32
MADISON SC		80						0					
MANITOWOC	MUNICIPAL	02	MTW		44 08	087 40	651A	0	15	11			
MARSHFIELD	MUNICIPAL	02	MFI		44 39	90 11	1261A	0	25				
MILWAUKEE	MITCHELL FIELD	10	MKE	72640	42 57	087 54	0693	41	24	11	4		
MILWAUKEE	TIMMERMAN	05	MWC		43 07	088 03	0745A	0	16	11			
MILWAUKEE LS		09		7253/	43 02	087 54	0585G	44					
MOSINEE	CENTRAL WISCONSIN	02	CWA		44 47	89 40	12731	C	17	11			
NEENAH		70						0					
OSHKOSH	WITTMAN FIELD	32	CSH		44 00	088 34	805A	C	18	11			
PARK FALLS		07	PKF	72741	45 56	090 27	1539	81					
PLUM ISLAND		09	3WI		45 19	86 57	577G	C					
RHINELANDER	ONEIDA CO	02	RHI		45 38	089 27	1608A	0	15	11			
SHEBOYGAN	SBM COUNTY MEM	02	SBM		43 46	87 51	746A	C	25				
SHEBOYGAN		09			42 45	87 42		42					
STEVENS POINT	MUNICIPAL	02	STE		44 33	89 32	1110A	0	15	12			
WAUSAU	MUNICIPAL	04	AUW		44 55	089 37	1196	0	24	11	8		
WISCONSIN RAPIDS	ALEXANDER FIELD	02	ISW		44 22	89 50	1019A	0	25				

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STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWL	RRT
WYOMING											
BIG PINEY		08	BPI	72577	42 32	110 07	6821	41	04 51		
CASPER	AIR TERMINAL	10	CPR	72569	42 55	106 28	5290	41	24 11 4	2	
CHEYENNE	MUNICIPAL	10	CYS	72564	41 09	104 49	6141	41	24 11 4	2	
CODY	MUNICIPAL	02	COD		44 31	109 01	5096A	0	12 11		
DOUGLAS		08	4DG	72568	42 45	105 23	4853	81	16 21 4		
EVANSTON	MUNICIPAL	03	EVW		41 20	111 00	6600A	0	24 11 8		
JACKSON	MUNICIPAL	02	JAC		43 36	110 44	6444A	0	12 11		
LANDER	HUNT	10	LND	72576	42 49	108 44	5558	41	24 11 4	222	
LARAMIE	GEN BREES	04	LAR		41 19	105 41	7272	0	24 11 8		
MOORCROFT		07	4MC	72663	44 16	104 57	4282	41			
NEWCASTLE	MONDELL FIELD	02	ECS		43 53	104 19	4165A	C	25		
RAWLINS	MUNICIPAL	04	RWL		41 48	107 12	6743	0	24 11 8		
RIVERTON	MUNICIPAL	02	RIW		43 03	108 27	5509A	0	25 21		
ROCKSPRINGS	MUNICIPAL	04	RKS		41 36	109 04	6745	0	24 11 8		
SHERIDAN	SHERIDAN COUNTY	14	SHR	72666	44 46	106 58	3968	21	24 11 2	2	
WORLAND	MUNICIPAL	04	WRL		43 58	107 58	4210	0	24 11 8		
ARCTIC											
EUREKA	ELLESMERE IS	90	YEU	72917	79 59	85 57	34	41		22	
ISACHSEN	ELLEF RINGNES I	90	YIC	71074	78 47	103 32	00A3	41	25	22	
MOULD BAY	PATRICK IS	90	YMD	71072	76 14	119 20	006F	41	16 41 8	22	
RESOLUTE BAY	INTNL	90	YRB	72924	74 43	094 59	0209	41	24 11 0	22	
T-3 FLETCHERS ICE IS		90					*	41	04 51 3	11	
ANTARCTIC											
AMUNDSEN SCOTT	SOUTH POLE	10	NPX	89009	90 00S		9186	41	04 51 4	11	
CARIBBEAN AND WEST INDIES											
BARBADOS		90	MKPB	78954				0		22	
BASSETERRE/ST KITTS		87	MKPK	78857	17 17	062 44	0029	43			
BLUEFIELDS		07	MNBL	78745	11 59	83 47	256	51			
CASTRIES/ST LUCIA		07	MKPL	78946	14 02	061 01	181	43			
CHARLOTTE AMALIE	TRUMAN	05	MIST	78543	18 20	064 59	0221	0	17 11		
CHRISTIANSTED	ALEX HAMILTON	05	MISX		17 42	064 48	0055	0	16 11		
CURACAO	DR PLESMAN	90	MACC	78988	12 12	68 59	278	0	24 11	22	
GRAND CAYMAN	OWEN ROBERTS FLD	90	MKCG	78384	19 17	081 22	6	0		22	
HAM BLUFF LS		39		78545	17 46	064 52	0072	23			

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WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PWD	RPT
CARIBBEAN AND WEST INDIES											
KINGSTON	PALISADOES	30	MKJP	78397	17 56	076 47	0024	0		22	
MAYAGUEZ	AIRPORT	03	MJMZ		18 15	067 09	0028	0	14 11		
PONCE	MERCEDITA	05	MJPS		18 01	066 34	49	0	17 11		
PUERTO CABEZAS		07	MNPC	78730	14 02	083 24	[illegible]	51		[illegible]	
RAIZET		90	MFFR	78897	16 16	061 31	0008	0		22	
ROSEAU/DOMINICA		07	MKPD	78907	15 19	061 24	0237	31			
SAN ANDRES IS		90	MCSP	001	12 35	081 42		0		22	
SAN JUAN	ISLA VERDE INTNL	40	MJSJ	78526	18 26	066 00	0062	81	24 11 0	222	XP3
SAN JUAN SC		40			18 26	66 04	045	0			
SANTO DOMINGO		90	MDSD	78486	18 29	069 53		0		22	
SINT MAARTEN	JULIANA	40	MACM	78866	18 03	063 07	10	0		11	
SWAN ISLAND		10	KSWA	78501	17 24	083 56	0035	81		22	
TRINIDAD		90	MKPP	78567	10 41	061 27		0		11	
OCEAN											
ATLANTIC STA B		90	4YB		56 30	051 00		0		42	
ATLANTIC STA C		90	4YC		52 45	035 30		0		42	
ATLANTIC STA D		90	4YD		44 00	041 00		0		42	
ATLANTIC STA E		90	4YE		35 00	048 00		0		42	
ATLANTIC STA H		90	4YH		38 00	071 00		0		42	
PACIFIC STA N		90	4YN		30 00	140 00		0		42	
PACIFIC STA V		90	4YV		34 00	164 00E		0		42	
PACIFIC ISLANDS											
AILINGLAPALAP		07		91367	07 16	168 50E	9	41			
EBON MI		07		91442	04 35	168 43E	09	41			
ENIWETOK		09	PKMA	91250	11 21	162 21E	106	41			
GUAM MARIANA IS		10	PGAC	91217	13 33	144 50E	0365	81	22 11 2	222	
JALUIT/JABOR IS MI		07		91369	05 55	169 39E	09	41			
JOHNSTON ISLAND		10	PJON	91275	16 44	169 31	0017	81	24 11 0	222	
KAPINGAMARANGI ECI		07		91434	01 05	154 49E	0013	21			
KOROR WCI		10	PTRO	91408	07 20	134 29E	0109	91	24 11 0	22	
KUSAIE/LELE IS ECI		07	PTSA	91356	05 20	163 02E	13	41			
KWAJALEIN	BUCHOLZ AAF	90	PKWA	91366	08 44	167 44E	0026	81	24 11 2	222	573
MAJURO MARSHALL IS	AIRPORT	10	PKMJ	91376	07 05	171 23E	0010	81	24 11 0	222	
MILI MARSHALL IS		07		91378	06 05	171 44E	14	41			
MURILO RUO IS ECI		07		91330	08 36	152 14E	10	42			
NAMONUITO ULUL I ECI		07		91322	08 35	149 40E	10	42			
NUKUORO ECI		07		91425	03 51	155 01E	0014	21			

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STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV	FD	A	PWU	RRT
PACIFIC ISLANDS													
PAGAN MARIANA IS		07	PGSN	91222	18 08	145 46E	0044	41					
PAGO PAGO	INTNL	10	NSTU	91765	14 20S	170 43	0010	81	24	11	2	222	
PINGELAP ECI		07		91353	06 13	160 42E	14	21					
PONAPE ECI		10	PTPN	91348	06 58	158 13E	0151	81	24	11	0	22	
PULUWAT IS ECI		07		91324	07 21	149 12E	15	42					
ROTA MARIANA IS	AIRPORT	02	PGRC		14 10	145 15E		0	07	12			
SAIPAN USCG LORAN		09		91232	15 08	145 42E	0012	41					
SAIPAN	KOBLER FIELD	02	PGSN		15 09	145 42E	0105	0	10	91			
SATAWAL WCI		07		91323	07 22	147 02E	0012	41					
SATAWAN ECI		07		91338	05 20	153 44E	0025	42					
SONSOROL WCI		07		91314	05 19	132 13E	0020	21	4	1			
SWAINS I LAND		07		91735	11 03S	171 05	0010	31					
TOBI WCI		07		91410	03 01	131 11E	0014	41					
TRUK ECI	MOEN	10	PTKK	91334	07 28	151 51E	0008	81	24	11	0	22	
UJELANG ATOLL MI		07		91343	09 46	160 59E	9	21					
ULITHI/FALALOP I WCI		07	PTUL	91203	10 02	139 49E	16	41					
UTIRIK MARSHALL IS		07		91258	11 14	169 51E	9	41					
WAKE ISLAND	INTERNATIONAL	40	PWAK	91245	19 17	166 39E	0012	81	24	11		222	
WOLEAI WCI		07		91317	07 23	143 55E	0012	41					
WOTJE MI		07	PKWO	91371	09 28	170 15E	9	41					
YAP WCI	AIRPORT	10	PTYA	91413	09 29	138 05E	0056	71	19	11		111	
SOUTH AMERICAN COOPERATIVE													
ANTOFAGASTA	CERRO MORENO	90	SCFA	85442	23 22S	070 28	0449	0				22	
BOGOTA	EL DORADO	90	MCBO	80222	04 42	074 09	8422	41	24	11	9	22	
GUAYAQUIL		90	SEGU	84129	02 12S	079 53		0	10	21		11	
IQUITOS		90						0					
ISLA DE PASCUA		90		85469	27 10S	109 26		0				11	
JUAN FERNANDEZ IS		90						0					
LA PAZ	EL ALTO	90			16 30S	68 10		0				11	
LIMA		90	SPIM	84628	12 01S	077 02	0442	0				11	
PUERTO MONTT	CHAMIZA	90	SCMO	85801	41 29S	072 51	0016	0				22	
PUNTA ARENAS		90						0					
QUINTERO	CHILEAN AFB	90	SCER	85543	32 44S	071 32	0023	0				22	
MEXICO													
CHIHUAHUA		90	CUU	76225	28 42	106 04	4684G	0				22	
EMPALME		90	GYM	76256	27 57	110 49	0036G	0				22	
GUADALUPE IS		90		76151	28 53	118 18	20G	0				22	

CHIHUAHUA		90	CUU	76225	28 42	106 04	4684G	0		22	
EMPALME		90	GYM	76256	27 57	110 49	0036G	0		22	
GUADALUPE IS		90		76151	28 53	118 18	20G	0		22	

WEATHER SERVICE OFFICES AND STATIONS

STATION NAME	AIRPORT NAME	TYPE	CALL	NO.	LAT.	LONG.	ELEV.	SC	AV FD A	PMU	RPT
MEXICO											
LA PAZ B C	AIRPORT	90	LAP		24 10	110 21	18	0		2	
MAZATLAN		90	MZT	76458	23 12	106 25	6	0		11	
MERIDA	INTNL	90	MID	76644	20 57	89 40	33G	0		22	
MEXICO CITY	INTNL	90	MEX	76679	19 26	099 05	7331G	0		11	
MONTERREY	AEREO PUERTO DEL N	90	MTY	76393	25 52	100 12	1476	0		22	
SOCORRO IS		90		76723	18 43	110 57	125	0		2	
VERACRUZ		90	VER	76692	19 09	096 07	43G	0		11	

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